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AGRICULTURAL SCIENCES

STUDY OF THE EFFECT OF SOWING RATES ON VEGETATIVE PARAMETERS OF "QISMƏT" TRITICALE VARIETY

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Abstract

The purpose of the research work is to study the productivity indicators of triticale plants under different sowing rates and plant densities in the soil-climatic conditions of the Ganja-Dashkasan region and to determine the optimal cultivation parameters. The object of the research work is the "Qismət" triticale variety. The subject of the research work is the impact of agrotechnical factors such as plant density and sowing rates on the development of triticale plants, yield elements and total grain yield. The research work was carried out in the experimental field at the "Grain and Legume" plants field laboratory of ASAU in 2024-2026. The field experiment was carried out using the classical precise sowing method, applying different sowing rates (3.5; 4; 4.5; 5 million seeds/ha) and plant densities. During the research, the productivity and biomorphological indicators of triticale plants under different sowing rates and plant densities will be analyzed comparatively. The results obtained will allow for the scientific determination of optimal triticale cultivation schemes in regional conditions. As a result of the research, the optimal sowing rate and plant density of triticale in regional conditions will be determined. This will allow for the provision of scientifically based recommendations to farmers and specialists working in the agricultural sector. The results obtained will serve to increase triticale productivity, reduce production costs and ensure agro-ecological sustainability.

Keywords: triticale, sowing rate, germination, survival rate, plant height, productive tillering.

Triticale is a new plant developed through the hybridization of wheat and rye. Breeding programs for triticale have been carried out and are ongoing in many countries, primarily in the USA, Poland, Canada, and Mexico. These studies aim to increase productivity per acre in nutritionally poor agricultural areas and thereby help meet the food demands of the rapidly growing global population. In triticale research, wheat is used as the maternal plant and rye as the paternal plant. Triticale's adaptability and productivity in arid regions come from wheat, while its ability to grow in cold, acidic, and saline soils is inherited from rye [5,7].

In areas where wheat and barley cannot be grown with high quality due to unfavorable soil conditions, triticale demonstrates a higher yield potential. Compared to wheat and barley, triticale is more tolerant to both nutritional and non-nutritional stress conditions. Globally, triticale is primarily used as a grain crop for animal feed. It is also cultivated for forage production and as pasture for livestock. Triticale is widely used as a grain source in poultry feed, with a feed quality comparable to that of maize, wheat, and barley. Of the three million hectares of triticale cultivated worldwide, approximately 80% is sown in the fall and 20% in the spring. In recent years, triticale flour mixed with high-quality wheat flour has also been used in the production of baked goods, cookies, bread, cakes, and pasta [6,11].

There are a total of 4.2 million hectares of triticale cultivation area worldwide. Of this, 80% is used for winter triticale cultivation, while 20% is for spring cultivation. The global average yield of triticale is 364 kg per day. In terms of cultivated area, Poland, Belarus, Germany, and France rank among the top producers. Globally, around 266,000 tons of triticale are exported, while 221,000 tons are imported [10].

As the world population continues to grow, food production must increase at the same pace. With arable land reaching its limit, scientists have been driven to achieve higher yields per unit area using existing crops, as well as to introduce new plant species capable of producing acceptable yields on poor soils and under various environmental stresses. Triticale, a hybrid of wheat and rye, is one of the first and most successful outcomes of such research. Globally, especially in developed countries, triticale is cultivated on approximately 2.9 million hectares. Of the total cultivated area, 80% is used for winter triticale and 20% for spring triticale [8].

Cereal crops such as wheat, barley, oats, rye, and triticale are primarily grown for their grains and used as human food, but they are also harvested for fodder and used as roughage feed. In the rest of the world, the use of cereals as animal feed is widespread. The feed obtained from these grains is given to animals in fresh, dried, or silaged for [1].

High-quality roughage production plays a key role in the development of forage crops and the livestock industry. However, feed and feeding costs, which make up a significant portion (60–70%) of the production stage in livestock farming, have a considerable impact on business profitability. In recent years, the use of cereal crops as green fodder within forage production has also been increasing proportionally [2].

Triticale is a hybrid plant species, artificially created by humans, that represents a new botanical genus within the Poaceae family. It combines the

beneficial traits of both wheat and rye. Progress in the breeding and cultivation of winter triticale depends on the existing genetic diversity, the method of incorporating desirable genes into superior genotypes, and the efficiency of selected genotypes and lines [3, 4, 9, 12].

In our experiment, the field germination of the "Qismət" variety according to the seeding rate variants was as follows: 63.6–79%, 74.8–81.7%, and 75.3–83.7%. Our data align with existing literature: as the seeding rate increases, the survival rate of plants decreases. At the same time, crops with high seeding rates thin out significantly.

According to Table 1, the highest germination percentage for the "Qismət" triticale variety was observed at a seeding rate of 3.5 million seeds/ha. Increasing the seeding rate from 3.5 to 5.0 million seeds/ha reduced germination capacity by approximately 8.6% (from 81.5% to 72.9%). Notably, when the seeding rate increased by 42% (from 3.5 to 5.0 million seeds/ha), the number of plants only increased by 28% (from 285 to 367 plants/m²). This indicates that the yield gained from each additional kilogram of seed sown decreases progressively. At a seeding rate of 5.0 million seeds/ha, the plant density reached its highest level (367 plants/m²). However, this density may negatively affect plant height growth and grain filling in the future, as the plants begin to shade each other. Thus, the conclusion is that the highest quality germination (percentage-wise) occurs at 3.5 million seeds/ha, while the highest quantity (number of plants) is achieved at 5.0 million seeds/ha.

As seen in Table 1, when the seeding rate is high (for example, 5.0 million seeds/ha), plant density in the field increases. As a result, competition for water, nutrients, and sunlight intensifies among plants, leading to the death of weaker plants. In dense sowings, air circulation weakens and moisture accumulates, increasing the risk of disease spread and thus reducing the survival rate. There is a 7.4% difference in survival rate (60.3% - 52.9%) between the sparsest seeding rate (3.5 million seeds/ha) and the densest seeding rate (5.0 million seeds/ha).

Looking at Table 1, despite increasing the seeding rate from 3.5 to 5.0 million (approximately 43%), the number of surviving plants only increased by 10.9% (from 174 to 193). This indicates that a large portion of the additional sown seeds is wasted. Nature itself regulates the density in the field. Although extra sown seeds may germinate, they cannot withstand competition during the growth period and die off. The 5.0 million seeds/ha rate requires higher costs (for seeds), but the number of plants remaining in the field does not differ significantly compared to the 3.5 million seeds/ha rate (the difference is only 19 plants/m²).

Based on the figures given in Table 1, analyzing the effect of seeding rates on the plant height of the “Qismət” triticale variety shows that plant height decreases as the seeding rate increases. This can be explained by several factors: 1. Reduction of nutrient area – As the seeding rate rises, the nutrient area available per plant decreases. This leads to weaker development of the root system and consequently the above-ground parts (height) of the plant. 2. Light and competition – In dense plantings, plants shade each other. The decrease in height from 139 cm to 131 cm indicates that excessive density hinders plants from reaching their full height potential. 3. Durability – Usually, taller plants (in sparse planting) have stronger stems. In very dense plantings, plants tend to be shorter and have weaker stem development.

Table 1. Effect of seeding rates on vegetative traits of "Qismət" triticale variety

Variants Seeding rates mln. seeds/ha	Seed germination rate	Number of germinated plants	Plant survival rate	Number of surviving plants	Plant height	Productive tillering
3,5	81,5	285	60,3	174	139	1,68
4,0	78,9	313	58,4	186	135	1,62
4,5	75,1	334	55,7	189	133	1,59
5,0	72,9	367	52,9	193	131	1,39

Table 1 also shows the effect of seeding rates on the total number of productive tillers per 1 m² in the "Qismət" triticale variety. This indicator reflects the field's final potential as a synthesis of both the seeding rate and the tillering capacity. It is evident from the table that increasing the seeding rate affects the number of productive stems per 1 m² in a nonlinear manner. The highest number of productive ears (stems) in the field was obtained at the seeding rate of 4.0 mln/ha. In this variant, the balance between the number of plants and the individual tillering capacity created the highest yield potential. When the seeding rate reached 5.0 mln/ha, the number of productive tillers sharply decreased to 267. This means that due to excessive density, some plants cannot produce productive stems or wither from weakness. Notably, at the 5.0 mln/ha variant, although more seeds were sown, the result (267) was even lower than at the sparsest seeding (293). This proves that excessive density directly causes yield loss.

From our research, we can conclude that as the seeding rate increases, the germination capacity and the number of germinated plants tend to decrease. The survival rate is inversely proportional to the seeding rate, meaning that as the seeding rate increases, the survival rate decreases. Although the number of surviving plants increases, plant height decreases with increasing seeding rate. Productive tillering shows better results at lower seeding rates. Overall, it is evident that the optimal seeding rate is strategically important for achieving high germination and survival rates as well as increased yield.

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ARTS

HOW ART, IDENTITY, AND INEQUALITY INTERSECT IN MODERN ECONOMIES

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Abstract

This article examines the intersection of art, identity, and inequality in modern economies, arguing that cultural production is deeply embedded within broader structures of economic power. Drawing on interdisciplinary literature from cultural economics, sociology, and political economy, the study analyzes how artistic value is socially constructed through markets, institutions, and symbolic recognition. The findings highlight persistent inequalities in access to cultural resources, visibility, and income, shaped by class, race, gender, and geography. While digital platforms and creative industries have expanded opportunities for participation, they have also intensified precarity and winner-take-all dynamics. The article further explores how recognition-based approaches to cultural inclusion often fail to address material disparities, limiting their transformative potential. By situating art within the political economy of inequality, the study emphasizes the need for institutional reform, redistributive policies, and alternative valuation frameworks that treat art as a public good rather than solely a market commodity.

Keywords: Art markets, cultural economy, identity, inequality, creative labor, cultural value

Introduction

In modern economies, art occupies a paradoxical position: it is celebrated as a space of creativity, freedom, and symbolic expression, yet it is deeply embedded in economic structures marked by inequality. Over the past several decades, cultural production has become increasingly central to economic growth, urban development, and global trade, giving rise to what scholars describe as the "cultural" or "creative" economy [16]; [5]. Art now circulates not only as a bearer of aesthetic or social meaning but also as a financial asset, a form of symbolic capital, and a tool of political and cultural influence.

Economic sociologists and cultural theorists have long argued that artistic value is not inherent but socially constructed through institutions, markets, and power relations [1]; [17]. Museums, galleries, critics, and funding bodies play a central role in legitimizing certain forms of art while marginalizing others, often reproducing existing hierarchies of class, race, gender, and geography. As a result, cultural markets tend to mirror broader economic inequalities rather than operate as meritocratic systems driven solely by talent or innovation.

Art is also a crucial medium through which identities are formed, represented, and contested. Cultural production shapes collective memory, national narratives, and social belonging, making it inseparable from questions of identity and recognition [15] . However, recognition in the cultural sphere is unevenly distributed. Artists from dominant social groups are more likely to receive institutional support and universal acclaim, while artists from marginalized communities are frequently framed through narrow identity categories that limit both their artistic autonomy and economic opportunities.

At the same time, the conditions of artistic labor reflect structural inequalities in modern economies. Creative work is often characterized by precarious employment, unpaid internships, project-based contracts, and high levels of income volatility [12]; [7]. These conditions disproportionately disadvantage individuals without access to economic security or social networks, reinforcing exclusion even as cultural industries present themselves as open and inclusive.

Recent technological changes have further complicated this landscape. Digital platforms and globalized markets have expanded access to cultural production and distribution, yet they have also introduced new forms of concentration and asymmetry. Algorithmic visibility, platform monopolies, and data-driven valuation systems shape whose art circulates and who benefits economically, often intensifying winner-take-all dynamics.

This article examines how art, identity, and inequality intersect in modern economies, arguing that cultural value is both a reflection of economic power and a mechanism through which inequality is reproduced. By synthesizing insights from cultural economics, sociology, and political economy, the article seeks to illuminate the structural forces shaping contemporary cultural markets while acknowledging art's potential as a site of critique and social transformation.

Methods

This study employs a qualitative, interpretive research design grounded in interdisciplinary scholarship from cultural economics, sociology of art, political economy, and inequality studies [13]. Given the conceptual nature of the research question—examining

how art, identity, and inequality intersect in modern economies—the study prioritizes theoretical synthesis and critical analysis over primary data collection. This approach is well suited to exploring structural patterns, institutional dynamics, and meaning-making processes that are not easily captured through quantitative methods alone.

The analysis draws on secondary sources, including peer-reviewed academic literature, foundational theoretical texts, policy reports, and empirical studies related to cultural markets, creative labor, and inequality. Sources were selected based on three criteria: (1) relevance to the economic organization of art and cultural production; (2) engagement with identity-based inequality (including class, race, gender, and geography); and (3) influence or recognition within their respective scholarly fields. Priority was given to works that have shaped contemporary debates in cultural economics and sociology.

The study integrates three complementary analytical lenses. First, a political economy perspective is used to examine how macroeconomic structures, market institutions, and capital concentration shape cultural production and distribution. Second, a sociological approach to cultural value draws on theories of symbolic capital, field dynamics, and institutional legitimacy to explain how artistic worth is constructed and recognized. Third, a recognition-based framework is employed to analyze how identity and cultural representation influence both symbolic and material outcomes for artists and cultural workers.

To ground the theoretical analysis, the study incorporates illustrative examples from global art markets, creative industries, and digital cultural platforms [14]. These examples are not treated as exhaustive case studies but as heuristic devices that demonstrate how abstract mechanisms operate in practice. Examples include high-end art markets, publicly funded cultural institutions, and platform-based creative economies [3]. The use of illustrative cases enhances analytical clarity without claiming empirical generalizability.

Results

Art as Economic Capital

Art functions as a form of economic capital through markets, institutions, and symbolic valuation. High-end art markets concentrate wealth among elite collectors, galleries, and financial intermediaries, transforming artworks into speculative assets. Cultural products gain value not only from intrinsic qualities but from institutional endorsement—museums, critics, and elite networks—which tend to privilege artists with existing social and economic capital. This dynamic reinforces inequality by limiting market access for marginalized creators.

Identity and Cultural Recognition

Art is a key medium through which individual and collective identities are expressed and recognized [6]. However, recognition is uneven. Artists from dominant social groups are more likely to have their work framed as "universal," while artists from marginalized backgrounds are often categorized as "ethnic," "political," or "local." This framing affects both cultural legitimacy and economic outcomes, shaping who receives funding, visibility, and long-term career stability.

Inequality in Creative Labor

Creative work is frequently characterized by precarious employment, unpaid labor, and winner-take-all dynamics. Individuals with financial safety nets are better positioned to absorb risk, intern without pay, or invest in self-promotion. As a result, inequality in broader economic structures translates directly into inequality within cultural industries, despite narratives that frame art as meritocratic or talent-driven [8].

Digital Platforms and New Asymmetries

Digital platforms have lowered barriers to entry for artistic production and distribution, but they have also created new forms of inequality. Algorithmic visibility, platform monopolies, and unequal access to digital infrastructure shape who benefits economically from cultural production. While some artists gain global audiences, most face intensified competition and declining income shares.

Discussion

The intersection of art, identity, and inequality highlights the limitations of viewing cultural markets as neutral or purely creative spaces [4]. The findings underscore that the relationship between art, identity, and inequality in modern economies is not incidental but structural. Cultural markets are embedded within broader systems of economic power, and the mechanisms through which artistic value is produced and distributed closely resemble those found in other unequal markets. Far from existing outside capitalism, art economies often amplify its core dynamics: concentration of wealth, gatekeeping by elite institutions, and winner-take-all outcomes.

One central implication of this analysis is that cultural inequality cannot be understood solely as a problem of representation. While visibility and symbolic recognition are crucial, they are inseparable from material conditions such as access to funding, labor protections, and market infrastructure. Recognition without redistribution risks becoming a symbolic solution to a material problem, particularly in creative industries where exposure is often offered in place of fair compensation. This finding aligns with broader critiques of cultural inclusion strategies that prioritize diversity in representation without addressing underlying economic disparities.

The role of institutions emerges as particularly significant. Museums, galleries, universities, funding agencies, and digital platforms function as arbiters of legitimacy, shaping not only artistic canons but also economic opportunity [9]; [10]. Although many institutions have adopted equity-oriented policies, their valuation practices often remain tied to market logics that privilege already established actors. This tension raises questions about whether institutional reform can occur without more fundamental changes in how cultural value is measured and rewarded.

Digitalization introduces both opportunities and constraints. Platform-based cultural production has expanded access to audiences and lowered entry barriers, yet it has also intensified precarity and competition. Al-

gorithmic systems reward scale, consistency, and engagement metrics, which often disadvantage artists producing experimental, community-based, or politically critical work. Moreover, platform monopolies extract value from creative labor while shifting risk onto individual producers, reinforcing inequality even as participation appears more open.

From a policy perspective, the findings suggest that market-based solutions alone are insufficient to address cultural inequality. Public funding for the arts, universal basic income experiments, stronger labor protections for creative workers, and alternative ownership models such as cooperatives offer potential pathways toward more equitable cultural economies. Importantly, such interventions must recognize art as a public good with social value beyond its market price.

The discussion also highlights art's ambivalent political role. While cultural production can challenge dominant narratives, articulate marginalized identities, and imagine alternative futures, it is simultaneously vulnerable to co-optation. Critical or oppositional art is frequently absorbed into market circuits, where its radical potential is neutralized through commodification. This tension does not negate art's transformative capacity but underscores the need to situate cultural resistance within broader political and economic movements.

Finally, this study points to several avenues for future research. Empirical studies examining income distribution, career trajectories, and institutional decision-making in cultural sectors would help quantify the patterns identified here. Comparative research across regions, particularly in the Global South, could illuminate how different political and economic contexts shape cultural inequality [11]. Further work is also needed to explore how emerging technologies—such as artificial intelligence and blockchain—may reshape cultural value and labor relations in ways that either reinforce or challenge existing inequalities.

In sum, understanding the intersection of art, identity, and inequality requires moving beyond celebratory narratives of creativity and innovation. It demands a critical examination of the economic structures that govern cultural production and a commitment to reimagining systems in which artistic expression and social equity are mutually reinforcing rather than in tension.

Conclusion

Art occupies a central yet contested position in modern economies, functioning simultaneously as a source of meaning, identity, and economic value. This article has shown that artistic markets are not neutral arenas of creativity but structured spaces shaped by power, institutional authority, and inequality. Cultural value is socially constructed in ways that often reproduce broader economic disparities, even as art retains the potential to challenge dominant narratives and imagine alternative futures. Addressing inequality in cultural economies therefore requires more than symbolic recognition; it demands material redistribution, institutional reform, and a redefinition of value that recognizes art as a public good rather than merely a market commodity.

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ECONOMIC SCIENCES

ECONOMIC INTERESTS AND ENVIRONMENTAL PROTECTION IN THE CONTEXT OF HUMAN RIGHTS: SEEKING BALANCE IN INTERNATIONAL LAW

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Abstract

The interplay between economic development and environmental protection has become a central concern in contemporary international law. While economic growth drives national and global prosperity, it often exerts significant pressures on natural resources, threatening ecosystems and, by extension, fundamental human rights. This article explores how international law seeks to reconcile these competing priorities by promoting sustainable development and safeguarding human dignity. Drawing on perspectives from both economics and law, the study examines legal principles, international treaties, and judicial decisions that demonstrate the ongoing struggle to achieve a balanced approach. The article argues that sustainable development, when understood as the integration of economic, environmental, and human rights considerations, is essential for equitable and long-term prosperity.

Keywords: Economic development, Environmental protection, Human rights, International law, Sustainable development, Environmental law, Economic interests, Transboundary environmental harm

Introduction. Economic development and environmental protection are frequently presented as conflicting goals. On one hand, economic growth fosters employment, improves standards of living, and fuels innovation. On the other hand, unregulated economic activity can degrade the environment, causing pollution, resource depletion, and climate change, which in turn negatively impact human health, social stability, and human rights. The challenge for policymakers, scholars, and international legal bodies is to identify mechanisms through which economic interests can be pursued without compromising environmental integrity or human well-being.

Human rights provide a crucial framework for this analysis. The recognition of a right to a healthy environment, either explicitly or implicitly in international law, emphasizes that environmental harm is not merely an ecological concern but a human rights issue. Access to clean air, water, and sustainable natural resources is integral to the enjoyment of other fundamental rights, including the rights to life, health, and an adequate standard of living. In this context, economic development must be assessed not only in terms of efficiency and growth but also with regard to its impact on the protection of human rights.

This article seeks to examine how international law mediates the relationship between economic interests, environmental protection, and human rights. By combining economic analysis with legal reasoning, it aims to provide a comprehensive understanding of the principles, challenges, and strategies necessary to achieve a sustainable and equitable balance.

Economic Interests and Environmental Protection: A Complex Relationship. Economic interests encompass a wide array of activities, including industrial production, international trade, investment, and technological innovation. These activities are essential for national prosperity and global development. However, they often generate negative externalities that compromise environmental integrity, such as pollution, deforestation, and the overexploitation of natural resources. The resulting environmental degradation can, in turn, undermine human rights by threatening access to clean water, adequate food, health, and safe living conditions.

Economic theory offers tools for understanding and mitigating these trade-offs. Cost-benefit analysis, for instance, can help policymakers evaluate the potential economic gains of an activity against the environmental and social costs it imposes. Concepts such as sustainable development and green growth provide a framework for aligning economic progress with environmental protection and human well-being. Yet, the practical application of these theories often faces obstacles, including short-term political pressures, insufficient regulatory mechanisms, and the challenge of assigning accountability for transboundary environmental harm.

International law plays a critical role in formalizing these trade-offs. Treaties, customary norms, and judicial decisions increasingly recognize that the pursuit of economic interests cannot justify environmental harm or the violation of human rights. This legal recognition is essential in promoting responsible economic behavior and creating incentives for sustainable practices.

Human Rights and Environmental Protection in International Law. The incorporation of environmental protection within the human rights framework has evolved significantly over the past decades. While foundational human rights instruments, such as the Universal Declaration of Human Rights (UDHR) and the International Covenant on Economic, Social, and Cultural Rights (ICESCR), do not explicitly refer to environmental protection, they enshrine rights that are directly affected by environmental degradation. The right to life, the right to health, and the right to an adequate standard of living are all undermined when the environment is compromised.

Subsequent international agreements and soft law instruments have explicitly linked environmental protection to human rights. The Rio Declaration of 1992 emphasized sustainable development as a human-centered approach that integrates economic growth, environmental stewardship, and social equity. Agenda 21 further underscored the responsibility of states and the international community to protect ecosystems in a manner consistent with human rights.

Judicial decisions have also contributed to this evolving framework. International courts and human rights bodies increasingly recognize that environmental harm can constitute a violation of human rights. For example, the Inter-American Court of Human Rights has addressed cases in which environmental degradation infringed on indigenous communities' rights to life, health, and cultural identity. Similarly, the European Court of Human Rights has acknowledged that severe environmental pollution may interfere with the enjoyment of private and family life under the European Convention on Human Rights.

These developments illustrate that environmental protection is not merely a matter of policy preference but a legal obligation intimately linked to human rights. The integration of human rights considerations into environmental law provides a normative framework for evaluating economic activities and ensuring that growth does not come at the expense of human dignity.

Achieving Balance: Challenges and Strategies. Despite growing recognition of the interdependence between economic interests, environmental protection, and human rights, achieving a balanced approach remains challenging. States often prioritize short-term economic growth over long-term environmental sustainability, particularly in contexts of political instability or economic scarcity. Environmental harm frequently transcends national borders, complicating accountability and enforcement. Multinational corporations, which play a central role in global economic development, often operate across jurisdictions with varying environmental and human rights standards, raising questions of corporate responsibility.

Addressing these challenges requires multifaceted strategies. Incorporating human rights and environmental impact assessments into economic policymaking can help ensure that development projects respect fundamental rights. International treaties and regulatory frameworks must be strengthened to hold states and corporations accountable for transboundary environmental harm. Sustainable investment strategies, guided by principles of corporate social responsibility and environmental, social, and governance (ESG) standards, can reconcile profitability with ethical obligations.

International cooperation and knowledge sharing are also critical. Cross-border agreements and partnerships can facilitate the exchange of best practices, technological innovation, and financial resources necessary for sustainable development. By fostering collaboration among governments, international organizations, civil society, and private actors, the international community can advance policies that harmonize economic growth with environmental stewardship and human rights protection.

Conclusion. The intersection of economic interests, environmental protection, and human rights presents a defining challenge for international law in the twenty-first century. While economic growth remains essential for prosperity, it must not be pursued at the expense of the environment or human dignity. Legal frameworks, informed by economic reasoning and human rights principles, are critical in shaping policies and practices that achieve a sustainable balance.

Ultimately, the pursuit of sustainable development requires a synergistic approach that integrates economic efficiency, environmental sustainability, and respect for human rights. By promoting accountability, fostering international cooperation, and encouraging responsible economic practices, international law can facilitate a development path that is equitable, resilient, and sustainable. The integration of human rights into environmental and economic policies is not only a legal imperative but also a moral and practical necessity for ensuring the well-being of current and future generations.

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JURISPRUDENCE

LEGAL BASES AND LIABILITY MECHANISMS FOR PROCESSING PATIENT HEALTH DATA IN GEORGIA: A COMPARISON WITH EUROPEAN STANDARDS

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Abstract

The present article examines the legal bases for processing patient personal data, especially health data, and the liability mechanisms in case of their violation in the context of medical activity. The research is based on normative-dogmatic and comparative-legal methods and combines European data protection standards, international human rights protection mechanisms and professional ethical norms, as well as Georgian national legislation and administrative practice.

The aim of the research is to systematically analyze the legal bases and liability framework for processing patient personal data in the context of medical activity, by identifying those legal mechanisms that ensure effective protection of patient data, and in case of violation - appropriate imposition of liability.

The normative model of technical and organizational obligations for health data processing in electronic systems is separately analyzed as a practical tool of legal control. The article structurally includes: (I) the status of health data; (II) the legal basis for data processing; (III) forms of liability and administrative response, including professional standards and regulation of electronic systems. The final part formulates recommendations for strengthening the real, and not only formal, provision of patient data protection and rights.

Keywords: health data; confidentiality; data processing; informed consent; public interest; professional ethics.

Introduction

In the modern healthcare system, the processing of patient personal data is one of the most sensitive and high-risk legal processes. Given the specifics of medical activity, patient health information includes data that are directly related to a person's private life and dignity. For this reason, patient health data is classified as a special category of personal data in modern legal systems and is subject to a strict legal protection framework.

The processing of patient personal data in medical activities is a legally regulated process that must be based on clearly defined legal grounds, professional standards and accountability mechanisms. Improper data processing may result in both a violation of the fundamental rights of the patient and the legal liability of the medical institution and personnel. Thus, the protection of patient data is considered not only in the context of protecting individual rights, but also in the context of public interest and patient safety.

The lawfulness of the processing of patient personal data cannot be limited to meeting formal requirements. It is necessary to assess the entire cycle of data processing - from data collection, storage and use, to their sharing and destruction. In this process, special importance is attached to the legal grounds for data processing, including professional obligations, public interest and informed consent of the patient, which does not constitute a universal or absolute guarantee for the lawful processing of data.

In the legal space of Georgia, the issue of the protection of patient personal data is regulated by both the legislation regulating the healthcare sector and the norms on the protection of personal data. However, practice shows that the relationship between data protection and medical activities is often assessed fragmentarily, and the mechanisms of responsibility are inconsistent. Particularly problematic is the superficial understanding of the role of informed consent, when the formal existence of consent automatically equates to the legality of data processing, despite the neglect of other legal requirements.

Chapter 1. Health data as a special category of personal data

1.1. Legal basis for the special status of health data

Health data is a special category of personal data, the processing of which is legally subject to an enhanced protection regime due to their high sensitivity and direct connection with fundamental human rights. These data reflect the physical and mental state of a person, the history of medical interventions and health risks, which directly connects them to the principles of privacy and human dignity. Accordingly, the processing of health data is permissible only on strictly defined legal grounds and in compliance with the principle of proportionality, since their unlawful disclosure or use creates a real threat of discrimination, social stigmatization and violation of patient autonomy. The World Medical Association's Lisbon Declaration on the Rights of the Patient establishes a modern medical-legal standard based on patient autonomy and justice. The document ensures the patient's right to quality medical care, informed decision and consent, confidentiality of information and respect for dignity, thus considering patient rights as a unified system of

professional ethics and positive obligations of the state.[1]

According to Article 8 of the Convention for the Protection of Human Rights and Fundamental Freedoms, the protection of private and family life is a fundamental right, within the framework of which information about a person's health also falls. This provision prohibits arbitrary interference by public authorities with this right and only allows interference in exceptional cases when it is carried out on the basis of law and is necessary in a democratic society, including to ensure the legitimate aim of health protection. This standard in the context of the processing of health data means that such interference is permissible only under strict conditions of lawfulness, necessity and proportionality, which creates a legal basis for enhanced protection of these data.[2]

The case law of the European Court of Human Rights also confirms that health information belongs to the most intimate sphere of private life and must be protected.[3]

1.2. European legal framework for the protection of health data

Within the European legal framework for the protection of health data, the processing of special categories of personal data, including health data, is prohibited in principle, reflecting the particular sensitivity of the information in question and the high degree of potential impact on fundamental human rights. At the same time, the legal regulation provides for exceptional cases when the processing of such data is permitted on strictly defined legal grounds, including on the basis of the explicit consent of the data subject, in cases of necessity for the protection of life and health, for important objectives of public interest or in the process of medical diagnosis, treatment and management of healthcare systems. These exceptions are based on the principles of proportionality and purpose limitation and are associated with the existence of additional guarantees, such as the protection of professional secrecy and the application of appropriate organizational and technical security measures.[4] Thus, the processing of health data is legally permissible only when it serves a legitimate purpose and the rights and interests of the data subject are adequately protected.

According to the European Union Agency for Fundamental Rights (FRA) Data Protection Law Guidance, health data are considered not only direct medical information, such as diagnosis, data on treatment or medical interventions performed, but also any information that directly or indirectly allows conclusions to be drawn about the physical or mental health of a person. Such data may include laboratory test results, genetic data, mental health records, information on the presence of chronic diseases or disabilities, as well as data related to the fact of the patient receiving medical care. This broad definition once again highlights the particular sensitivity of health data and justifies the existence of an enhanced legal protection regime for them.[5]

The Oviedo Convention considers health data as an integral part of the inviolability of private life and establishes the right of an individual to the protection of health information, as well as the right to know the data collected about him or her or, if he so wishes, to refrain from receiving them. At the same time, the Convention does not establish the absoluteness of health data protection: it allows restrictions on the exercise of rights only on the basis of law and only when this is necessary in a democratic society, including for legitimate public health purposes. As a result, the processing of health data is subject to the principles of lawfulness, purposefulness and proportionality.[6]

1.3. National Legal Framework for Health Data Protection

According to the Georgian legal framework, health data are considered a special category of personal data and are subject to enhanced legal protection. The Law of Georgia on Personal Data Protection defines health-related information, as well as genetic and biometric data, the processing of which is related to the unique identification of a natural person, as a special category of data. The aforementioned law broadly defines the concept of health data and includes not only information about the physical or mental health of a person, but also any data related to the fact of providing medical services, including in cases where such data indirectly allow conclusions to be drawn about the state of health. This normative approach reflects the legislator's assessment of the special sensitivity of health data and justifies the need for stricter legal protection for them. At the same time, the law considers the processing of special categories of data to be permissible only in the presence of strictly defined legal grounds and additional guarantees for the protection of the rights and interests of the data subject, thus the processing of health data is associated with the observance of the principles of legality, necessity and proportionality.[7]

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[1] World Medical Association, ***WMA Declaration of Lisbon on the Rights of the Patient***, 2022. https://www.wma.net/policies-post/wma-declaration-of-lisbon-on-the-rights-of-the-patient/?utm_source (10.01.2026).

[2] European Convention on Human Rights, Rome, 4 November 1950, Article 8. https://fra.europa.eu/en/law-reference/european-convention-human-rights-article-8-0?utm_source (10.01.2026).

[3] Z v. Finland, no. 22009/93, ECHR, 1997 https://hudoc.echr.coe.int/eng#{%22itemid%22:[%22001-58033%22]} (10.01.2026).

[4] Regulation (EU) 2016/679 (GDPR), Article 9. https://gdpr-info.eu/art-9-gdpr/ (10.01.2026).

[5] European Union Agency for Fundamental Rights, *Handbook on European Data Protection Law*, 2018, https://fra.europa.eu/en/publication/2018/handbook-european-data-protection-law-2018-edition (10.01.2026).

[6] Council of Europe, Convention on Human Rights and Biomedicine (Oviedo Convention), ETS No. 164, 4 April 1997, Articles 10 and 26. https://rm.coe.int/168007cf98 (10.01.2026).

[7] Law of Georgia "On Personal Data Protection", 2023, Articles 3,4,6

According to the Law of Georgia "On Patients' Rights", medical records and any information about the patient related to diagnostics, treatment or the fact of providing medical services constitute confidential information, the protection of which is the obligation of the medical service provider both during the patient's lifetime and after his or her death. Disclosure of health data is permissible only in strictly defined cases, including with the patient's consent, in the event of the necessity to protect the life or health of a third party, or on other grounds directly provided for by law. In addition, the law, in parallel with the protection of confidentiality, develops the patient's right to information and decision-making, which creates a close connection between the protection of health data and the realization of patient autonomy. The patient has the right to determine to whom and in what volume information about his health condition is provided, and the provider of medical services is obliged to provide information taking into account the patient's ability to perceive and to use a minimum of special terminology.[8] Such Georgian regulation once again confirms that health data is considered in Georgian law as information of particular sensitivity, the processing of which is related to the observance of the principles of legality, necessity and proportionality. The mentioned norms present the national model of health data protection as a complex legal institution oriented on the rights of the patient.

The Law of Georgia "On Health Protection" considers the issue of health data protection not only in the context of the individual rights of the patient, but also as an integral element of the ethical and professional framework of medical activity. The law defines medical (medical) secret as information that a doctor and other medical personnel receive in the process of professional activity about the patient's physical and mental condition, personal and family life, as well as the fact of providing medical care. This construction emphasizes that the protection of health data is not only a formal requirement of confidentiality, but also an ethical obligation of the medical profession, the violation of which entails legal liability.[9] Thus, the legal regime for the protection of health data in the field of health care is based on a common principle of respect for human dignity, patient autonomy and professional responsibility.

1.4. Doctrinal foundations of health data protection (Faden & Beauchamp)

The scientific literature emphasizes that the special legal status of health data is determined not only by their sensitive content, but also by the context in which they are processed. According to Faden and Beauchamp, the medical relationship is characterized by a structural power asymmetry between the doctor and the patient, where the patient is often in a physically, psychologically and informationally vulnerable position. In such conditions, the processing of a patient's health data is associated with an increased risk of their misuse and violation of patient autonomy, which justifies the existence of a strengthened legal regime for data protection. Accordingly, the confidentiality of health data and strict legal control over their processing are considered not only as a technical regulation, but also as a necessary tool for protecting the patient's dignity and self-determination.[10]

The considered normative and doctrinal analysis confirms that health data are considered in modern legal systems as a special category of personal data, the protection of which is based on the principles of human dignity and inviolability of private life. The synthesis of international and national regulations demonstrates that the protection of health data is a complex legal institution based on patient autonomy and professional responsibility and is not limited to technical requirements of confidentiality. Accordingly, the processing of such data is permissible only with strict observance of the principles of legality, purposefulness and proportionality.

Chapter 2. Legal bases for processing patient personal data in medical activities

2.1. Differentiation of legal bases: general bases and special categories of data

The processing of patient personal data, especially health information, in medical activities is permissible only if there are strictly defined legal bases. Modern data protection law rejects a single or formal legitimization of data processing and establishes the principle that each processing operation requires an independent, clearly defined and foreseeable legal basis. This approach is particularly strict in relation to special categories of personal data, among which patient health data occupy a central place.[11]

The systematization of legal bases in European data protection law is most fully established in the General Data Protection Regulation (GDPR), which clearly distinguishes between general legal bases for data processing and additional conditions for processing special categories of data, thus clearly indicating that the processing of health data cannot be satisfied solely by the presence of the patient's will or administrative expediency.[12] Data processing in medical activities is legitimate only if both general and specific legal requirements are met simultaneously.

https://www.matsne.gov.ge/ka/document/view/5827307?publication=8 (10.01.2026).

[8] Law of Georgia on "Patient's Rights", 2000, Articles 27, 28, 21, 19 https://www.matsne.gov.ge/document/view/16978?publication=16 (10.01.2026).

[9] Law of Georgia "On Health Protection", 1997, Articles 3, 4, 42. https://www.matsne.gov.ge/document/view/29980?publication=62 (10.01.2026).

[10] Faden, R. R., Beauchamp, T. L., *A History and Theory of Informed Consent, Oxford University Press,* 1986. https://archive.org/details/historytheoryofi0000fade/page/n5/mode/2up?utm_source (10.01.2026).

[11] European Union Agency for Fundamental Rights, *Handbook on European Data Protection Law*, 2018, https://fra.europa.eu/en/publication/2018/handbook-european-data-protection-law-2018-edition (10.01.2026).

[12] Regulation (EU) 2016/679 (GDPR), Article 6, 9. https://gdpr-info.eu/art-6-gdpr/ https://gdpr-info.eu/art-9-gdpr/ (10.01.2026).

One of the main legal bases in the medical field is the fulfillment of a legal obligation. Medical institutions and healthcare professionals are obliged to maintain patient medical records, store diagnostic and treatment data, and ensure access to information for the purposes of supervision and accountability. Such processing is not based on the patient's consent, but on the existence of a public-legal obligation and constitutes an independent legal basis for data processing.[13]

The second important legal basis is related to the necessity of protecting life and health, which becomes particularly relevant in emergency medical care, critical situations and cases where the patient is unable to express his/her will. The legal logic is based on the principle that the protection of life and health constitutes the highest legal value, which justifies the processing of personal data without consent, but only under strict proportionality conditions.[14] This basis is widely recognized in both European and national legal frameworks.

The third legal basis is related to the public interest in the field of health protection. Public health surveillance is a form of state responsibility, the implementation of which often requires the systematic collection, analysis and sharing of personal data, since the implementation of public health policies, epidemiological control, disease prevention and ensuring the efficiency of the healthcare system are impossible without the processing of a certain amount of patient data. In such cases, data processing is permissible without informed consent, provided that it serves a clearly defined legitimate aim, is carried out proportionately and is accompanied by effective legal and institutional safeguards to prevent data misuse. Thus, data processing justified in the interest of public health does not abolish the requirement for the protection of privacy, but develops it within the framework of a legal model based on responsibility.[15]

2.2. Public interest

The case-law of the European Court of Human Rights confirms that health data, especially sensitive medical information, constitute one of the most protected areas of private life. In the case of Z v. Finland, the Court emphasised that the confidentiality of health data constitutes an essential element of Article 8 of the Convention for the Protection of Human Rights and Fundamental Freedoms and that its restriction is permissible only when there is an overriding public interest and strict legal safeguards are provided to prevent abuse. According to the Court, the disclosure of health data, including for the purposes of criminal proceedings or the protection of public health, cannot be legitimate automatically and requires a strict proportionality test. Thus, the case-law of the Court confirms that the processing of data justified by public interest does not override the principle of confidentiality, but requires its balancing with the effective protection of individual rights.[16]

2.3. Informed consent

Informed consent is one of the, but not universal, legal bases for data processing. The institution of informed consent is considered in modern medical law as a legal expression of patient autonomy and personal self-determination, which ensures the patient's participation in the decision-making process.[17] Its function is not limited to the formal provision of information, but also includes a level of communication with the patient that enables a real understanding of the content, risks and alternatives of medical intervention.[18]

In the Georgian legal system, informed consent of the patient is established as one of the fundamental prerequisites for the legality of medical intervention and an important tool for protecting patient rights.[19] The Georgian Law on Health Protection links informed consent to the voluntary acceptance of medical intervention by the patient or his/her legal representative on the basis of appropriate information and establishes its mandatory nature in various medical processes, including treatment, diagnostic, rehabilitation, preventive and palliative care. In the same context, the Georgian Law on Patient Rights considers informed consent as the result of a patient's informed decision, which is based on receiving complete information about the nature of the medical service, risks, expected consequences and alternative options, and in the case of minors, the participation of their legal representative.[20]

The Georgian Law on Personal Data Protection links informed consent to the legal regime for protecting the confidentiality of patient health data and considers it as one of the important grounds for data processing in relation to special categories of data.[21]

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[13] General Medical Council (UK), *Confidentiality: good practice in handling patient information*, 2017 https://www.gmc-uk.org/ethical-guidance/ethical-guidance-for-doctors/confidentiality (10.01.2026).

[14] Council of Europe, *Convention on Human Rights and Biomedicine (Oviedo Convention),* ETS No. 164, 4 April 1997, Articles 10 and 26. https://rm.coe.int/168007cf98 (10.01.2026).

[15] World Health Organization, *Ethical issues in public health surveillance,* 2017 https://www.asset-scienceinsociety.eu/sites/default/files/9789241512657-eng.pdf?utm_source (10.01.2026).

[16] Z v. Finland, no. 22009/93, ECHR, 1997 https://hudoc.echr.coe.int/eng#{%22itemid%22:[%22001-58033%22]} (10.01.2026).

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[18] Morton, S. Janula, M. Quarto, C. *Trenfield, Sarah. Informed consent: do we have an obligation to double check?* National Library of Medicine, 2024, DOI: 10.1016/j.bja.2024.09.013. https://pubmed.ncbi.nlm.nih.gov/39426920/ (10.01.2026).

[19] Law of Georgia "On Health Protection", 1997, Article 22, 23 https://www.matsne.gov.ge/document/view/29980?publication=62 (10.01.2026).

[20] Law of Georgia on "Patient's Rights", 2000, Articles 4-6 https://www.matsne.gov.ge/document/view/16978?publication=16 (10.01.2026).

[21] Law of Georgia "On Personal Data Protection", 2023, Articles 6,8,9

The draft European Health Data Space (EHDS) Regulation also confirms that the patient's consent and the ability to refuse data processing do not constitute an absolute legal barrier, as the processing of health data for the purposes of public health, scientific research and policy development is permissible within the framework of exceptions defined by law.[22]

Chapter 3. Forms of liability and administrative response in case of violation of the protection of patient personal data

3.1. Systemic framework of liability

Illegal or improper processing of patient personal data, especially health data, in medical activities gives rise to multi-level legal liability. Modern data protection law considers liability not only as an instrument of sanction, but also as an instrument of prevention and accountability. In this context, the liability framework includes administrative, civil and disciplinary responses, and in severe cases - criminal liability.[23]

In the medical sector, administrative liability is often associated with violations such as: non-existent or incorrect legal basis for data processing; formal use of consent without its freedom and revocation; violation of the principles of data minimization and purposefulness; improper technical and organizational security measures.[24]

Administrative liability is the central mechanism for responding to data protection breaches. The GDPR establishes a model of independent supervisory authorities, which are empowered to monitor, issue binding instructions and impose administrative sanctions on data processors.[25] According to the Regulation, the sanction must be effective, proportionate and dissuasive, which emphasizes the preventive function of administrative response.[26]

3.2. Georgian administrative practice

In the legal space of Georgia, administrative response is carried out by the State Service for Personal Data Protection. National legislation does not limit violations of data processing rules to a declaration of principles and establishes a clear mechanism of administrative liability. In particular, the law distinguishes between separate liability for: violation of data processing principles, data processing without legal basis, and processing of special categories of data (including health data) without basis, which, through the severity of the sanction, emphasizes the high-risk nature of health data processing. The sanctioning system is differentiated according to the type of entity and economic scale (annual turnover up to/above 500,000 GEL) and provides for both warnings and fines, as well as increased liability in the presence of aggravating circumstances.[27]

In addition, the law extends liability not only to violations of the "basic" rules, but also to specific obligations that are particularly relevant in the medical field: compliance with video/audio monitoring rules, rules for processing data of deceased persons, violation of data subject rights, failure to comply with the obligation to inform, violation of security obligations, failure to comply with the obligation to notify and inform about an incident,[28] and obstruction of the activities of the supervisory authority or failure to comply with a request.[29] As a result, the law creates a complex framework for administrative response, where a violation of patient data protection is assessed not only from an ethical or civil-legal perspective, but also as a real instrument of public-legal liability, which obliges medical institutions and professionals to conduct data processing processes in advance in a legal manner.

The practice of the State Service for Personal Data Protection clearly shows that the processing of personal data of patients, especially health information, in the healthcare sector is subject to strict legal control and cannot be legitimized either by the reputational interest of the institution or by a general reference to the public interest. Both the disclosure of a patient's medical record to a third party as a result of inadequate security and the public discussion of the patient's health status by doctors during a press conference constituted the processing of a special category of data in violation of the requirements of the law.[30]

A brief overview of two specific cases is important to illustrate national administrative practice:

Case I - Disclosure of a patient's medical card: Based on the application of the data subject, the Personal Data Protection Service investigated the fact of a possible disclosure of a patient's personal data by a private clinic. During the inspection, it was

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https://www.matsne.gov.ge/ka/document/view/5827307?publication=8 (10.01.2026).

[22] Szikley, J. *European Health Data Space,* ("EHDS") https://journal.pdps.ge/doc/%E1%83%9F%E1%83%A3%E1%83%A0%E1%83%9C%E1%83%90%E1%83%9A%E1%83%98%201-2%20(2025)%20244-251.pdf (10.01.2026).

[23] European Union Agency for Fundamental Rights, *Handbook on European Data Protection Law*, 2018, https://fra.europa.eu/en/publication/2018/handbook-european-data-protection-law-2018-edition (10.01.2026).

[24] World Health Organization, *Ethical issues in public health surveillance*, 2017, https://www.asset-scienceinsociety.eu/sites/default/files/9789241512657-eng.pdf?utm_source (10.01.2026).

[25] Regulation (EU) 2016/679 (GDPR), Article 6, https://gdpr-info.eu/art-6-gdpr/ (10.01.2026).

[26] Regulation (EU) 2016/679 (GDPR), Article 83 https://gdpr-info.eu/art-83-gdpr/ (10.01.2026).

[27] Law of Georgia "On Personal Data Protection", 2023, Articles 66-68 https://www.matsne.gov.ge/ka/document/view/5827307?publication=8 (10.01.2026).

[28] Law of Georgia "On Personal Data Protection", 2023, Articles 69-79 https://www.matsne.gov.ge/ka/document/view/5827307?publication=8 (10.01.2026).

[29] Law of Georgia "On Personal Data Protection", 2023, Articles 86-87 https://www.matsne.gov.ge/ka/document/view/5827307?publication=8 (10.01.2026).

[30] State Service for Personal Data Protection, *Processing of Personal Data in the Healthcare Sector (Case Review),* 2023 https://pdps.ge/ka/content/980/7252/jandacvis-seqtorSi-personaluri-monacemebis-damuSaveba (10.01.2026).

established that a photograph of the first page of the patient's inpatient medical card, which contained the patient's personal number, first and last name, contact information, name of the medical institution, date of admission to the clinic and other identifiable data, was sent to the patient by a third party via a social network. The Service determined that the clinic failed to ensure proper data security measures, which is why it was held administratively liable under Article 46, Paragraph 1 of the Law of Georgia on Personal Data Protection. In addition, it was established that the natural person processing the data processed the data for clearly personal purposes, which is why the law did not apply to the said action.[31]

Case II – Disclosure of patient data during a press conference – The Personal Data Protection Service, based on a notification, examined the legality of the clinic's disclosure of the patient's personal data during a press conference. As a result of the inspection, it was determined that the clinic's doctors publicly disclosed the patient's personal data, including information about his health condition. The Service determined that some of the information disclosed during the press conference had not previously been publicly known and the clinic possessed the most recent data on the patient's health. In addition, the patient's written consent to the disclosure of the data did not exist, and in accordance with the requirements of Article 6 of the Law of Georgia "On Personal Data Protection", the disclosure of special categories of data without consent is not permitted. Based on the above, the clinic was held administratively liable for the violation provided for in Article 45 of the same Law.[32]

3.3. Georgian Judicial Practice

Georgian judicial practice on the issue of informed consent of the patient is limited, although individual decisions of the Supreme Court of Georgia emphasize the procedural, rather than formal, nature of consent. In one case, the court attached importance to the fact that the patient signed the consent document several hours before the operation, in an unstable psycho-emotional state, and concluded that the obligation to inform had not been properly fulfilled (SUSS, No. AS-645-2019).[33] In another case, despite the existence of a consent form, the court found that the patient was not informed about a possible serious complication of the operation, which actually developed after the operation (SUSS, No. AS-253-2021).[34] This practice confirms that consent should be assessed as a process of informing, and not only the existence of a written document.

3.4. Disciplinary liability and professional standards

Violation of the protection of a patient's personal data in medical practice often goes beyond legal liability and directly concerns standards of professional ethics and integrity, since confidentiality is recognized as a fundamental principle of modern medical ethics and is an integral part of a doctor's professional responsibility.

Identifiable information about a patient's health is considered an essential element of privacy, the protection of which is an integral part of a doctor's professional responsibility.[35]

Respect for the dignity, autonomy and rights of the patient is the core of the primary professional duty of the doctor, while the protection of confidentiality is a necessary prerequisite for a doctor-patient relationship based on trust. Special importance is attached to informed consent, which the Code considers not only as a prerequisite for medical intervention, but also as a legal and ethical guarantee of the patient's independent decision-making. At the same time, the Code clearly emphasizes the personal accountability of the doctor for the professional decisions made, the obligation to avoid conflicts of interest and the strict limitation of data disclosure only in cases of voluntary consent or exceptional ethical necessity. The above principles create the basis for disciplinary liability even in cases where the violation of patient data protection does not reach the threshold of administrative or criminal liability, which confirms that professional ethics in the field of medicine acts as an independent, but responsibility-oriented regulatory mechanism.[36]

The confidentiality of a patient's personal data is both an ethical and legal obligation for medical personnel and serves to prevent the misuse of personal information. The standard developed by the UK's General Medical Council (GMC) obliges doctors to use only the minimum amount of data necessary, ensure the appropriate management and protection of patient information, and define in advance clear and justified criteria for possible disclosure of data. In addition, each decision on the use or sharing of data must be made taking into account the patient's rights and the principle of voluntary consent. The GMC's approach does not reduce confidentiality to just technical control over information, but links it to the doctor's personal professional responsibility for the entire data processing process, which strengthens professional order and helps to strengthen patient trust in the healthcare system. According to the document, deviations from confidentiality, including data disclosure, are permissible only in cases expressly provided for by law, in the presence of significant public interest or special necessity for patient safety, and always require strict legal and ethical justification.[37]

3.5. Criteria for the effectiveness of administrative response

[31] Ibid.
[32] Ibid.
[33] Ruling of the Civil Cases Chamber of the Supreme Court of Georgia. No. AS-645-2019. 2019.
[34] Ruling of the Civil Cases Chamber of the Supreme Court of Georgia. No. AS-253-2021. 2021.
[35] World Medical Association*, Declaration of Lisbon on the Rights of the Patient,* adopted 1981, reaffirmed 2015, https://www.wma.net/policies-post/wma-declaration-of-lisbon-on-the-rights-of-the-patient/ (10.01.2026).
[36] World Medical Association, *International Code of Medical Ethics*, 1949 (rev. 2022) https://www.wma.net/policies-post/wma-international-code-of-medical-ethics/ (10.01.2026).
[37] General Medical Council, *Confidentiality: good practice in handling patient information,* 2017

The effectiveness of the liability system in the field of patient personal data protection is not determined only by the severity of the sanctions imposed. The consistency of the administrative response, legal predictability, and a risk-oriented approach that takes into account the nature of the violation, the sensitivity of the data, and the vulnerable status of the patient are of decisive importance. Such an approach provides not formal, but real protection and the preventive function of liability in medical activities.[38]

Disclosure of health information is permissible only in the presence of a specific and overriding public interest and requires a strict proportionality test, as such data are directly related to the patient's dignity, autonomy and trust in the health system.[39]

The EHDS Regulation strictly limits the secondary use of health data and prohibits their use for discriminatory decisions, commercial marketing or other incompatible purposes, which underlines the preventive role of administrative supervision.[40]

Chapter 4 - Technical and Organizational Obligations in Electronic Systems

4.1. Electronic Health Record System (EHR)

Electronic Health Record System (EHR) - The legality of health data processing in practice is closely linked to the normative framework for the functioning of the Electronic Health Record System (EHR). According to the current rule, the state is defined as the owner of the EHR, and access to the system is differentiated according to the roles of users, including the functional authority of the doctor, patient and authorized user. Access to the system is allowed only within the framework of the appropriate authorization and authority, which ensures the purposefulness of data processing and compliance with the principles of minimization. The same rule strengthens the technical elements of accountability, including the maintenance of a user register and logging of access to the system, which makes it possible to further control and legal verifiability of the data processing process.[41]

4.2. Register of Persons with Disabilities

The electronic system of the Register of Persons with Disabilities is a specialized model of health data processing, which is based on strict differentiation of access. The functioning of the system is organized by the so-called "pages" model, within which different subjects — including the system owner, the authorized person of the medical institution, the doctor and the data subject — are granted different and purposefully limited access rights. Of particular importance is the fact that the doctor has access only to his own patient's data, which directly reflects the implementation of the "need-to-know" principle in practice and reduces the risk of improper use or excessive availability of health data.[42]

4.3. Electronic Prescriptions

The electronic prescription circulation rule for pharmaceutical products (medicinal products) of the second group, Form No. 3, is **a special normative model for the processing of personal health data**, which establishes a centralized circulation of electronic prescriptions, within which access to data is differentiated according to the functional roles of users (doctor, pharmacist, patient) and is carried out only on the basis of appropriate authorization and professional authority. In addition, the electronic prescription system provides for the recording (logging) of the data processing process, access control and information storage rules, which ensures the technical and organizational foundations of data security, accountability and administrative supervision and strengthens the legal regime for the protection of health data.[43]

The electronic prescription system for prescription of psychotropic drugs and medicinal products equivalent to pharmaceutical products under special control, Form No. 2, is functionally linked to the electronic prescription circulation rule of Form No. 3, which ensures a unified, transparent and controlled model for processing highly sensitive health data. Such regulation enhances the traceability and accountability of data processing and demonstrates that health data protection in Georgia is implemented not only through the general data protection law, but also through special sectoral digital regulations.[44]

Conclusion

https://www.gmc-uk.org/ethical-guidance/ethical-guidance-for-doctors/confidentiality (10.01.2026).

[38] Regulation (EU) 2016/679 (GDPR), Article 5,6,9,83 https://eur-lex.europa.eu/eli/reg/2016/679/oj (10.01.2026).

[39] European Court of Human Rights, Z v. Finland, no. 22009/93, Judgment of 25 February 1997 https://hudoc.echr.coe.int/eng?i=001-58033 (10.01.2026).

[40] Szikley, J. *European Health Data Space,* ("EHDS") https://journal.pdps.ge/doc/%E1%83%9F%E1%83%A3%E1%83%A0%E1%83%9C%E1%83%90%E1%83%9A%E1%83%98%201-2%20(2025)%20244-251.pdf (10.01.2026).

[41] "On Determining the Procedure for the Operation and Production of the Electronic Health Records System (EHR)" Order No. 01-1/N of the Minister of IDPs from the Occupied Territories of Georgia, Labor, Health and Social Protection of January 3, 2019, https://www.matsne.gov.ge/ka/document/view/4390457?publication=11 (10.01.2026).

[42] "On Approval of the Rules for the Operation and Maintenance of the Electronic System of the Register of Persons with Disabilities" Order No. 7/N of the Minister of IDPs from the Occupied Territories of Georgia, Labor, Health and Social Protection of January 31, 2024 https://www.matsne.gov.ge/ka/document/view/6090865?publication=0 (10.01.2026).

[43] "On Approval of the Rules for Circulation of Form No. 3 Electronic Prescription for Pharmaceutical Products (Medicinal Products) Belonging to the Second Group" Order No. 01-29/N of the Minister of Labor, Health and Social Protection of Georgia of July 26, 2016, https://www.matsne.gov.ge/document/view/3329318?publication=9 (10.01.2026).

[44] "On Approval of the Rules for Circulation of Electronic Prescription Form No. 2 for Psychotropic Medicines and Medicinal Products Equivalent to Pharmaceutical Products Subject to Special Control" Order No. 01-31/N of the Minister of IDPs from the Occupied Territories of Georgia of April 8, 2022, https://www.matsne.gov.ge/ka/document/view/5433415?publication=1 (10.01.2026).

The present study has confirmed that the processing of patient health data in medical practice is a high-risk legal process that is directly related to the protection of human dignity, privacy and patient autonomy. A comparative analysis of international and national legal frameworks reveals that health data are considered a special category of personal data in modern legal systems, the processing of which is permissible only under strictly defined legal grounds and under conditions of enhanced protection.

The study has shown that informed consent, despite its fundamental importance, cannot act as a universal legitimizer of health data processing and cannot abolish the principles of purposefulness, minimization and security of data. The formal existence of consent does not exclude the responsibility of the data processor and requires an assessment of its procedural, voluntary and substantive nature.

The case law of the European Court of Human Rights and European data protection standards confirm that the confidentiality of health data is one of the most intensive areas of privacy protection and its restriction is permissible only by passing a test of overriding public interest and strict proportionality, which excludes the automatic legitimization of data processing by a general reference to public interest.

The analysis of the administrative practice of Georgia has shown that violations of patient data protection are in most cases related to the improper legal and organizational arrangement of data processing processes, which is why administrative liability functions not only as a sanctioning but also as a preventive mechanism.

Finally, the study confirms that the effective implementation of patient health data protection requires the unified and systematic operation of legal, institutional and technical-organizational mechanisms and cannot be limited to meeting formal normative requirements.

In view of the above, it is advisable to formulate recommendations that ensure the real and effective implementation of data protection principles in medical practice:

- **Differentiation of informed consent** - It is recommended to clearly separate the informed consent of the patient from other legal grounds for data processing. Consent should be assessed as a procedural legal mechanism and not as a universal basis for data processing, especially in relation to special categories of data. This approach is based on the principles of legality and accountability and reduces the risk of formal use of consent.
- **Institutionalization of the proportionality test** - When processing health data in the public interest, it is recommended to systematically apply the proportionality test, which includes an assessment of the legitimate aim, necessity and scope of the restriction. This test should become a standard tool for both administrative and judicial control, which is consistent with the approach established by the case law of the European Court of Human Rights.
- Strengthening the principle of accountability - Data processors should be obliged not only to comply with data protection rules, but also to prove their compliance. This includes prior documentation of data processing processes, logging of access, regular review of security measures and risk-oriented management.
- **Legal integration of technical and organizational measures** - It is recommended to directly link technical and organizational security measures with legal requirements when operating electronic systems (EHR, registries, electronic prescriptions). This ensures traceability of data processing, administrative control and effective implementation of responsibility.
- **Strengthening professional ethics and disciplinary responsibility** - The protection of patient health data should be considered not only as a legal issue, but also as a matter of professional ethics. It is recommended to actively use disciplinary mechanisms in cases where a data protection violation does not reach the threshold of administrative or criminal liability, but violates the patient-trust relationship.

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MEDICAL SCIENCES

THE IMPACT OF COMMUNICATION STRATEGIES ON PATIENT TRUST IN THE PRIVATE HEALTHCARE SECTOR: A LITERATURE REVIEW

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Abstract

Background: Patients' trust is a fundamental cornerstone of healthcare systems' effectiveness. In the private sector, where competition prevails, communication drives patients' loyalty.

Objective: This article analyzes the influence of various communication models on patient trust in private medical institutions.

Methods: This study uses systematic literature review methods. I retrieved more than nineteen academic articles, reports from various international organizations, and studies on medical management published over the last 15 to 20 years from Google Scholar and PubMed databases.

Results: The literature review identifies three primary factors that have the greatest impact on patient trust: the physician's empathetic and non-verbal communication, the transparency of medical services' pricing and processes, and the availability of digital communication channels such as medical portals and social media.

- The transparency of medical services' pricing and medical processes.
- The availability of digital channels of communication (medical portals, social media).

Researchers have found that the "patient-centered" approach increases patient trust compared to the traditional "paternalistic" approach.

Conclusion: Management of the communication strategy directly increases the competitiveness of private clinics. In the Georgian case, leaders emphasize transparency of information. This transparency reduces patients' skepticism toward commercialized medicine. Clinic managers should establish training systems.

Keywords: Patient trust, communication strategy, private healthcare, literature review, Georgia.

Introduction

This article explores communication strategies in the private health care market and their impact on patient trust. In a highly competitive market like health care, trust is a vital component that affects a clinic or health care facility's reputation. The literature review is based on three specific dimensions: interpersonal communication between the doctor and the patient, the efficiency of digital communication mediums, and transparency. The study draws on international literature and its applicability to emerging markets such as Georgia. It is observed that a patient-centered communication style, coupled with empathy, has a profound impact on perceptions of health care quality.

The healthcare sector cannot run smoothly unless patients and medical staff build trust. Trust serves as an essential therapeutic component that shapes patient outcomes and satisfaction with the medical system. In modern medicine, technology shapes doctor-patient interactions, and the main challenge is maintaining trust.

However, the problem of trust becomes even more complex within the private health care system. In the latter case, the patient is expected not only to receive health services but also to be the "consumer" who pays for them and has high expectations regarding their quality. In the private health care system, competition is on the rise; thus, the organization must regard trust as an important competitive advantage. In the patient's mind, there may be skepticism toward the private health care system, which may be perceived as more interested in profit than in the patient's best interests; here, the key function of the communication strategies becomes apparent.

The scope of the communication strategy within private healthcare delivery is not limited to merely conveying information through the physician. Rather, this involves a multidimensional approach that ranges from interpersonal relationships grounded in patient-centeredness to institutional transparency and the use of digital technologies. The literature review above reveals that the communication channels and methods selected are directly related to patients' feelings of safety and security.

The main objective of the current article was to identify the communication strategies that most strongly impact the patient's trust through a critical analysis of the relevant literature. In this regard, the current paper seeks to address the following question: how can communication management change the patient's experience to foster a high level of trust in a competitive environment? Thus, according to the model developed by Street et al. (2009) [1], if communication is successful, then "proximal outcomes" (e.g., under-

standing, trust, and agreement) will ensue, and as a result, the patient will comply more closely with the treatment regimen and will have more adequate self-care abilities. The authors suggest that the therapeutic effect of communication should be maximized to achieve intermediate outcomes, such as trust and social support, which will affect the patient's physical condition.

In studies of communication strategy, Richard Street and colleagues developed a key framework (Street et al., 2009). They argue that communication's effect on health is indirect and that trust is a crucial intermediate factor. More specifically, a doctor who manages patient emotions and shows empathy forms a strong alliance and gives the patient more "agency" and empowerment [1].

Hong highlights trust as a mediator. In this study, Hong notes that patients lack adequate medical knowledge to make an objective judgment of physicians' skill levels. Hence, they make a judgment on service quality based on interpersonal communication. The mediating effect of trust is greater among patients who make frequent visits to medical facilities.e, especially those with chronic illnesses, communication is a decisive factor.

The impact of applying the Patient-Centered Communication (PCC) approach is clearly reflected in the study by Hong (2012), which is based on the conceptual model by Epstein & Street (2007). According to the author, trust serves as a bridge connecting communication with quality perception. It should be noted here that since the patients in question have limited medical knowledge in most cases, the professionalism of the physician cannot be gauged by the precision in the diagnosis itself, but by the quality of the explanation provided in the diagnosis, as well as the recognition of the patient's emotional status.

The available literature indicates that Patient-Centered Communication (PCC) serves as the foundation for trust. According to the Epstein and Street (2007) model, trust acts as a proximal antecedent to treatment effectiveness. PCC may be defined in terms of the physician's capacity to address two essential patient needs: information (explanation of diagnosis) and emotions.

Research (Wanzer et al., 2004; Stewart, 2001) has shown that PCC factors like 'active listening,' involvement of patients in Shared Decision-Making, and 'the use of plain language in explanations' are all correlated with 'trust level.' It is interesting to note that 'empowerment of patients' and 'involvement in decision-making' function as a 'principal indicator of service quality in the private sector.'

A major goal of a communication strategy is to minimize uncertainty. According to McCormack (2011), meeting emotional needs (empathy) is as important as meeting informational needs (diagnosis) because a perception of vulnerability destroys trust [2]. As the following literature review indicates, Patient-Centered Communication (PCC) is not only a morally justifiable approach but also a financially sound strategy in the private sector. Studies by Epstein et al. (2005) and Stewart et al. (2000) clearly indicate that communication minimizes unnecessary diagnostic inv. Managing uncertainty is important (Wanzer et al., 2004). Management of uncertainty is important (Wanzer et al., 2004). Patients often visit clinics with high stress levels. If a physician ignores a patient's emotional needs, trust is broken, regardless of skill. Trust then becomes a direct result that determines behavior and quality judgments.

Wanzer et al. (2004), in their research based on Berger's (1987) Uncertainty Reduction Theory, argue that social interaction between the patient and the physician helps reduce anxiety. The use of Patient-Centered Communication (PCC) styles by the physicians helps in decreasing the patient's uncertainty, resulting in higher patient satisfaction and trust. [3]

Based on the literature review conducted in the current study, there is a clear relationship between patient satisfaction/trust and the physician's people skills. According to Flocke et al. (2002), when a physician portrays themselves as an approachable specialist with a personalized approach to health care, he/she earns substantially higher patient trust. This is due to the patient's perception of the physician's benevolence as a manifestation of the physician's deep understanding of the patient's problems.

Noteworthy in this respect is the discovery by Bellet and Maloney (1991), which suggests that empathy serves as the primary driver of trust development. Thus, when the patient feels that the physician understands his/her emotional situation, it becomes easier to comply with medical recommendations (Adherence). In this respect, the PCC dimensions of active listening, sufficient time allocation, and respect emerge as primary tools for developing trust in the private healthcare sector (Finney Rutten et al., 2006).

However, Pearson and Raeke (2000) argue that interpersonal trust can develop only through repeated interactions. McWhinney (1993) views each consultation as "a brief episode in a continuous relationship" that needs time to develop and mature. Therefore, the mediating effect of trust is substantially stronger among patients who repeatedly consult the same doctor. [4]

The current literature also supports the view that the aforementioned factor of trust is not static but rather a recursive, cumulative process (Epstein & Street, 2007). Studies show that the impact of Patient-Centered Communication (PCC) on perceptions of service quality passes through the filter of trust. Studies by Fiscella et al. (2004) and Thom (2001) found that trust increased when the physician corroborated patients' concerns and prompted them to ask more questions. [4]

However, it is worth noting that the mediator effect of trust is directly proportional to the number of visits. Pearson & Raeke (2000) posit that expectations can be continually evaluated only through repeated interactions. In the private health care market, a long-term communication strategy involving ongoing interactions with patients is a sure way to secure a very high perception of service quality. Analysis of the research results indicates that the outcome directly relates to trust formation and visit frequency.

In a study of 3,273 participants, trust has been shown to function as a full mediator in the perception of quality of service. Regarding private medical institutions, this shows that investing in staff's communication

skills will not only increase patient satisfaction but also reduce legal risks and unnecessary clinical costs. Additionally, communication will enable a physician to correct erroneous information commonly found on the internet, a major challenge in 21st-century healthcare.

However, in the modern era, patient-centered communication has moved beyond the doctor's office into the digital space. In fact, Hawn's seminal paper, "Take Two Aspirin and Tweet Me," published more than 10 years ago, foresaw the promise of social media in transforming the healthcare landscape into an open, more interactive system.

There is a clear association between digital health tools and eHealth and the development of a higher level of patient engagement. Ratna (2018) argues that the use of technology can facilitate patients' assumption of an active role in managing their health. This is considered a fundamental condition for trust—patient empowerment—in the Epstein and Street (2007) framework. Mobile health (mHealth) applications are considered crucial for achieving higher patient engagement. Tully et al. (2018) conducted a study showing that constant accessibility and rapid information exchange via MHealth applications can reduce patients' anxiety and increase their trust in their medical provider.

It should be noted that the importance of online communication has significantly grown in the post-pandemic period. Thus, in the context of online consultations (telemedicine) characteristic of the post-COVID-19 period, Luo et al. (2020) noted that trust could be built online if the rules of empathetic online communication were followed. At the same time, in the context of private clinics, social media has become an essential tool in assessing the patient's emotional state. Thus, Denecke & Neelamegham (2017) noted that analyzing patient reviews on social networks could better meet consumer emotional needs to build trust.

Besides improving physician-patient communication and reducing healthcare costs, the use of online healthcare platforms also directly affects patients' emotional dependence and service quality. The patient's emotional dependency and service quality will eventually ensure a strong physician-patient relationship.

In the private healthcare industry, building trust is closely related to the principles of Relationship Marketing. As Peltier et al. (2003) stated: "Marketing in healthcare services should extend beyond advertising to include long-term relationship development based on trust between patients and healthcare providers; this relationship is the key benchmark for the strength of a clinic's brand." Berry (1995) emphasized: "Trust is the foundation on which service quality is developed in the service industry; patients do not just purchase a procedure or treatment; they purchase a promise of quality." Moreover, the level of trust in relation to private clinics often manifests itself in dual form.

The extent of trust bestowed upon private clinics may be seen as having dual characteristics. Studies by Hardie and Critchley (2008) show that patients tend to trust private health care in terms of its "technological capabilities" and "service speed," though there are concerns about a lack of "financial transparency" in certain situations. In this context, it can be seen that the SERVQUAL model adopted by Lin and Lin (2011) also supports the notion that "perceived service quality" and "patient loyalty" are closely dependent on the clinic's demonstration of "reliability" and "empathy" as well. [11,12]

Trust management assumes special significance in crisis situations. During crisis situations, such as medical or service failures in the clinic, the trust repair strategy identified by Gillespie et al. (2012) becomes significant for the clinic. Transparency in communication, accountability, and issue resolution would be significant for maintaining the clinic's reputation as a private clinic. [13,14]

Regional and Cultural Aspects: Global Experience and Georgia

From this point of view, it should be noted that there is limited evidence and experience in Georgia; however, based on the research conducted in Western cultures, it can be stated that the level of patient trust is significantly influenced by the cultural context. It has been reported that patient expectations regarding communication also show cultural differences: Western cultures tend to emphasize patient autonomy, while traditional cultures value physician authority (Beukers et al., 2014). It often creates a balance between physician authority and patient autonomy (Skirbekk et al., 2011).

Quality improvement strategies in health care in Europe (WHO Reports, 2020-2023) highlight that "the patient-centered approach represents a universal standard to be applied regardless of regional characteristics." Timmermans (2020) argues that in modern medicine, "trust is increasingly 'technologically mediated,' meaning that physicians' authority is no longer only rooted in their professional expertise but also in their competence in using modern technologies and in transparent forms of communication." [15,16,17]

Moreover, within the Georgian Republic, the key determinants of trust in the private sector, according to findings on patient satisfaction (e.g., the National Center for Disease Control (NCDC) and local universities), are the speed of service and the infrastructure provided. Nevertheless, the lack of emotional satisfaction drives the patient to change clinics regularly. In the Georgian Republic, trust is an unstable entity owing to financial constraints; thus, the need for open communication that helps the patient be perceived not as the "client" but rather the "partner" in the process becomes imperative. [18, 19]

Methodology

This study is theoretical-conceptual, grounded in a critical literature review. The research process included three main stages: data retrieval, selection, and thematic analysis.

Data sources and search strategy: A literature search was conducted across international academic databases, including Google Scholar, PubMed, ScienceDirect, and ResearchGate. In addition, official reports of international organizations (WHO, NCI) and local government agencies (NCDC) were used.

The search was conducted using relevant keywords related to the topic, and nineteen (19) scientific sources were selected for the final analysis. In the selection process, priority was given to:

Studies that directly link communication strategies with patient trust and perceived service quality. We used papers published in the last 15–20 years, although "classical" theories of service marketing were also included (e.g., Berry, 1995).

The literature search was processed using thematic synthesis. The information was divided into several themes: interpersonal communication models, the impact of digital technologies, business ethics, and cultural characteristics. The findings from each source were synthesized and aligned with Epstein and Street's (2007) conceptual framework, which emphasizes trust as a mediating variable in the healthcare system.

Results

The literature synthesis and thematic analysis revealed several fundamental regularities related to the relationship between patient-centered communication (PCC) and trust:

1. Trust, as the foundation of communication, was found to be the research analysis showed that although PCC directly affects the perception of healthcare quality, this relationship changes significantly when the trust factor is introduced. It was found that, for patients who visit the clinic frequently, trust acts as a full mediator.

2. The effectiveness of digital communication, the analysis of online healthcare platforms, and social media revealed that:

• Online consultations and communities increase the patient's emotional attachment to the doctor.

• The use of digital channels leads to the optimization of medical procedures and significantly reduces healthcare costs for the patient.

• Patient satisfaction with digital interactions directly contributes to improving the doctor-patient relationship

3. In terms of business results, relationship marketing for the private sector revealed that:

• Understanding the quality of service (reliability, empathy, responsiveness) directly determines patient loyalty.

• A high level of trust plays a huge positive role in crisis situations, which positively affects the rating of clinics

4. Cultural and regional characteristics are important. Using Georgia as an example, a comparison of WHO reports and local data (NCDC) showed that, across the post-Soviet space, including Georgia, trust is closely related to financial transparency. Providing information in "plain language" and involving the patient in the decision-making process are considered high service standards that enhance competitiveness in the private sector and positively affect a medical institution's overall rating.

Discussion

The aim of our literature review was to assess the impact of patient-centered communication (PCC) on healthcare quality. The literature analysis highlighted that trust is not only a facilitating factor in communication but also a key argument in the patient's assessment and perception of healthcare quality.

1. Our findings clearly show that maintaining a "loyal patient" for private clinics depends more on trust than on technical infrastructure. When patients trust the provider, they become less critical of minor shortcomings and are more focused on long-term adherence to treatment.

2. The discussion revealed that digital technologies not only optimize resources and costs, which is economically beneficial for the private sector, but also meet the emotional needs of the patient, creating a feeling that the doctor is constantly available, which reduces patient dissatisfaction and increases the reputation of the private sector.

3. The process of building trust in the private sector often faces the challenge of "commercialization", which is caused by relationship marketing, because the clinic perceives the patient not as a partner but as a client. In Georgia, where treatment costs are high, the trust factor is considered an ethical criterion.

4. Practical recommendations for clinics:

Based on the research, it is advisable for private clinics to:

• PCC training: retrain doctors not only in medical expertise, but also in "soft skills."

• Digital integration: improve online feedback systems to strengthen trust.

• Transparency policy: provide detailed explanations of financial and medical decisions in order to increase patient engagement.

Conclusion

In this study, PCC is shown to form the fundamental foundation of efficiency in the private healthcare industry. The literature review confirms that trust, as a factor in physician–patient relations, is a strategic tool that significantly influences perceptions of medical service quality and patient satisfaction.

This research has several critical conclusions: The Decisive Role of Trust: Trust acts as a total mediator between PCC and quality assessment, especially in repeated visits. This implies that a clinic's success depends on its technological equipment and the emotional relationship it builds with the patient.

Benefits of Digital Communication: Online platforms and tools reduce uncertainty and treatment costs. This significantly increases patients' emotional dependence and loyalty.

Sustainability of the Private Sector: Empathy-based and transparent communication reduces the need for defensive medicine. This also lowers associated legal risks and helps guarantee the private sector's sustainability.

Finally, in the 21st-century healthcare system, with its abundance of information and high levels of competition, the development of patient trust will be the principal form of competitive advantage for private healthcare institutions. The models described in this chapter will serve as a basis for Georgian private healthcare institutions to place greater emphasis on developing healthcare staff's communication capabilities.

Author Contributions

- **Gulnara A.:** Conceptualization, methodology, and project administration.
- **Salome A.:** Literature search, data curation, and formal analysis.

- **Mishiko Gabaidze:** Visualization, investigation, and software/digital tools analysis.
- **Tengiz Taktakishvili:** Supervision, validation, and critical review and editing of the manuscript.

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PHILOLOGICAL SCIENCES

BILINGUALISM AND CHILDREN'S ACQUISITION OF THIRD AND FOURTH FOREIGN LANGUAGES: COGNITIVE, LINGUISTIC, AND EDUCATIONAL PERSPECTIVES

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Abstract

In the context of increasing globalization and linguistic diversity, bilingualism has become a common characteristic of childhood. Many bilingual children are subsequently introduced to third and fourth foreign languages through formal education. While bilingualism is widely associated with cognitive and linguistic benefits, its role in facilitating or constraining additional language acquisition remains a topic of academic debate. This article examines how bilingualism influences children's learning of third and fourth foreign languages by analyzing cognitive mechanisms, cross-linguistic interaction, and educational conditions. Drawing on research in psycholinguistics and multilingual education, the study identifies both advantages—such as heightened metalinguistic awareness and learning efficiency—and challenges, including language interference, cognitive overload, and insufficient pedagogical support. The findings suggest that bilingualism generally enhances multilingual learning outcomes when appropriate instructional strategies and supportive sociocultural environments are in place.

Keywords: bilingualism, multilingual children, third language acquisition, fourth language learning, language education

Bilingualism has increasingly been recognized as a natural and widespread phenomenon rather than an exceptional linguistic condition. Due to migration, intercultural communication, and multilingual educational policies, many children grow up using two languages in their daily lives. In addition to managing two linguistic systems, these children are often expected to learn further foreign languages as part of school curricula, particularly in regions where multilingual competence is valued.

Traditionally, language acquisition research focused primarily on monolingual learners acquiring a second language. However, this framework no longer adequately reflects the linguistic realities of modern classrooms. Bilingual children approach new languages with prior linguistic experience, which fundamentally alters the process of learning a third (L3) or fourth (L4) language. According to Cenoz (2003), multilingual learners do not simply repeat earlier stages of language learning; instead, they develop new strategies based on accumulated linguistic knowledge.

At the same time, the presence of multiple languages in a child's cognitive system raises important questions. Does bilingualism automatically facilitate additional language learning, or can it create obstacles such as interference and confusion? How do educational practices respond to the needs of multilingual learners? Addressing these questions is essential for understanding multilingual development and improving language education. This article explores the impact of bilingualism on children's acquisition of third and fourth foreign languages. By synthesizing existing research, the paper aims to provide a balanced analysis of both the benefits and the challenges associated with multilingual language learning in childhood.

One of the most influential perspectives on bilingualism emphasizes its cognitive benefits. Research has consistently shown that bilingual children develop enhanced executive functions, including attentional control, problem-solving skills, and mental flexibility (Adesope et al., 2010). These abilities emerge from the constant need to manage two linguistic systems and select the appropriate language in different contexts. From a multilingual learning perspective, these cognitive skills are highly relevant. Learning a third or fourth language requires sustained attention, the ability to recognize patterns, and flexibility in applying linguistic rules. Bilingual children are often better equipped to meet these demands because they have already developed strategies for navigating linguistic complexity.

Metalinguistic awareness refers to the ability to reflect on language as an abstract system rather than merely using it for communication. Bilingual children typically demonstrate higher levels of this awareness than monolingual peers, as they are exposed to different ways of expressing meaning (Bialystok, 2001). When learning additional foreign languages, metalinguistic awareness allows children to analyze grammatical structures, compare languages, and understand that linguistic rules vary across systems. This awareness is particularly advantageous in formal educational settings, where explicit instruction plays a central role.

Research suggests that bilingual children often learn additional foreign languages more efficiently than monolingual learners. One key reason is their familiarity with the language learning process itself. Having already acquired two languages, bilingual children tend to possess effective learning strategies, such as identifying patterns, using contextual clues, and drawing comparisons between languages. Positive transfer is

another important factor. Linguistic similarities between known languages and the target language can facilitate vocabulary acquisition, grammatical understanding, and pronunciation. For example, a bilingual child who speaks two Indo-European languages may find it easier to learn a third language from the same family due to shared syntactic and lexical features (Cenoz & Jessner, 2009).

Furthermore, research in multilingual development indicates that bilingual children frequently exhibit a higher tolerance for ambiguity compared to their monolingual peers. This heightened tolerance stems from their habitual navigation between two linguistic systems, requiring them to interpret and negotiate meaning from varied and sometimes conflicting language cues. As a result, bilingual learners are generally more comfortable encountering unfamiliar linguistic forms, novel syntactic structures, or unexpected usage patterns in an additional language. This psychological resilience can reduce anxiety associated with language learning and simultaneously enhance sustained motivation, both of which are recognized predictors of successful language acquisition in educational psychology (Dewaele & Li, 2021).

At the same time, the interaction among multiple languages within a single learner's cognitive system is not always straightforwardly facilitative. While cross-linguistic transfer — the process by which knowledge of one language influences the learning of another — can lead to positive outcomes such as accelerated vocabulary acquisition or structural inference, it may also produce **interference effects.** Interference occurs when features from a previously acquired language unintentionally surface in the use of another, manifesting in areas such as pronunciation, word order, and morphosyntactic accuracy. For example, phonological patterns from a first or second language can influence a child's articulation of sounds in a third or fourth language, resulting in non-target-like pronunciation (Jarvis & Pavlenko, 2020).

Moreover, interference is not limited to pronunciation; syntactic structures that differ across languages may be inappropriately generalized, leading to atypical sentence constructions or transfer of incorrect grammatical rules. For instance, a bilingual learner whose dominant language follows Subject–Object–Verb order might temporarily apply this pattern when producing sentences in a subsequent language with a Subject–Verb–Object structure, leading to non-target-like patterns in early stages of learning (Herdina & Jessner, 2002). Importantly, contemporary research frames these interference phenomena as natural developmental stages rather than inherent deficits, emphasizing that multilingual learners gradually refine interlanguage boundaries and internal control mechanisms as exposure and proficiency increase (Jessner, 2008).

However, contemporary research emphasizes that such interference should be viewed as a normal developmental phenomenon rather than a deficit (Jessner, 2008). Over time, multilingual learners learn to regulate cross-linguistic influence and develop clearer boundaries between their languages. Importantly, the extent of interference often depends on instructional quality. Teaching approaches that explicitly address similarities and differences between languages can reduce confusion and promote deeper understanding.

Despite the advantages of bilingualism, learning multiple foreign languages can place significant cognitive demands on children. Cognitive overload may occur when learners are exposed to several languages simultaneously without sufficient reinforcement or practice. This challenge is particularly evident in educational systems where curriculum time is limited. If exposure to each language is insufficient, children may struggle to achieve balanced proficiency. As Cummins (2000) notes, strong foundational skills in the first and second languages are essential for successful multilingual development.

Educational context plays a crucial role in shaping language learning outcomes, particularly for bilingual and multilingual children. Many existing language programs are still largely designed around monolingual norms and do not sufficiently acknowledge the complex linguistic repertoires that bilingual learners bring to the classroom. As a consequence, instructional practices often overlook students' prior knowledge, treating each new language as an isolated system rather than as part of an interconnected multilingual framework. This approach may prevent bilingual children from fully utilizing their existing linguistic resources, such as metalinguistic awareness and cross-linguistic transfer strategies. When instruction fails to build on these strengths, learning may become less efficient and learner motivation may decline. Therefore, educational programs that recognize and integrate bilingual learners' linguistic backgrounds are more likely to promote successful acquisition of third and fourth foreign languages.

Sociocultural factors are equally influential together with education. Parental attitudes, societal language policies, and the perceived prestige of each language affect children's motivation and confidence. When multilingualism is valued and supported, children are more likely to develop positive attitudes toward learning additional languages. In this framework, age of acquisition remains an important variable in multilingual learning. Younger children tend to acquire pronunciation more naturally, while older learners often benefit from greater cognitive maturity and literacy skills (De Angelis, 2007). Effective pedagogy should therefore be age-appropriate and learner-centered. Research supports instructional approaches that integrate languages rather than treating them as isolated systems. Encouraging comparison, reflection, and strategic language use helps children manage multilingual complexity more effectively.

Teacher training is another critical point in the teaching process to the bilingual students. Educators must be equipped to understand multilingual development and adapt teaching methods accordingly. Teacher training plays a pivotal role in the success of multilingual education. Educators must be adequately prepared to understand the cognitive, linguistic, and sociocultural dimensions of multilingual development in children. Without sufficient training, teachers may rely on

instructional practices designed for monolingual learners, which can limit the academic potential of bilingual and multilingual students. Effective teacher education programs should therefore include theoretical knowledge of bilingualism and third language acquisition, as well as practical strategies for managing cross-linguistic influence in the classroom. Furthermore, teachers need to develop the ability to adapt teaching methods, materials, and assessment practices to learners with diverse linguistic backgrounds. When educators are trained to recognize multilingualism as a resource rather than a challenge, they are better positioned to foster inclusive learning environments that support the acquisition of third and fourth foreign languages.

Bilingualism provides a strong foundation for the acquisition of third and fourth foreign languages in childhood, offering both cognitive and linguistic advantages. Enhanced executive functions, metalinguistic awareness, and prior experience with language learning equip bilingual children with strategies that facilitate the understanding of novel grammatical structures, vocabulary, and phonological patterns. Furthermore, their increased tolerance for ambiguity and psychological resilience contribute to sustained motivation and reduced anxiety when encountering new languages, promoting more effective language acquisition overall.

In addition, multilingual learning is not taught without challenges. Cross-linguistic interference, cognitive overload, and limited instructional support can impede progress if not adequately addressed. Educational contexts that fail to recognize the unique linguistic repertoires of bilingual learners may unintentionally constrain their learning potential. Similarly, sociocultural factors, including parental attitudes, societal language policies, and the relative prestige of each language, influence motivation and achievement. Effective teacher training, age-appropriate pedagogy, and multilingual-aware curricula are therefore critical in supporting successful third and fourth language acquisition.

Overall, the evidence suggests that bilingualism is a valuable resource rather than a barrier in multilingual development. With targeted educational strategies, supportive sociocultural environments, and informed teaching practices, children can leverage their bilingual experience to acquire additional languages more efficiently and confidently. Future research should continue to investigate the interplay between cognitive, linguistic, and sociocultural factors in multilingual learning, providing insights that can inform curriculum design, teacher preparation, and policy development for increasingly diverse classrooms.

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TECHNICAL SCIENCES

MODELS OF INTERACTION BETWEEN MICROCONTROLLER DEVICES AND CLOUD INFRASTRUCTURE IN DISTRIBUTED SYSTEMS

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Abstract
The article examines modern models of interaction between microcontroller-based devices and cloud infrastructure within distributed systems. Architectural approaches such as Device-to-Cloud, Device-to-Gateway-to-Cloud, and Edge/Fog Computing are analyzed, defining the principles of integrating low-level devices with high-level IT platforms. The impact of data transmission protocol selection (MQTT, HTTP/HTTPS, message brokers) on system reliability, security, and scalability is emphasized. Particular attention is given to issues of energy efficiency, fault tolerance, and data flow management. Examples of technology implementation in industrial and corporate IoT infrastructures are provided. The results of the study demonstrate the necessity of a comprehensive approach to architecture design that unites hardware, software, and cloud components.

Keywords: microcontroller, distributed systems, Internet of Things, cloud technologies, Device-to-Cloud, Device-to-Gateway-to-Cloud, Edge/Fog Computing.

Introduction

The development of distributed computing systems and the rapid proliferation of Internet of Things (IoT) devices necessitate the formulation of effective models for interaction between microcontroller-based devices and cloud IT platforms. New microcontrollers with their lower-level computational abilities are increasingly being integrated into advanced information and control systems where fault tolerance and scalability of real-time data exchange are needed. Combining such devices with advanced cloud facilities introduces a set of technical challenges related to security, fault tolerance, and configurability of the evolving conditions of distributed environments.

The objective of this study is to analyze models of interaction between microcontroller-based devices and cloud infrastructure within distributed systems, considering the requirements of reliability, security, and scalability.

Main part. Technological basis for the integration of microcontroller devices into distributed cloud systems

Distributed systems represent a collection of autonomous components that interact over a network to achieve a common goal – the collection, processing, and analysis of real-time data. The main properties of such systems include heterogeneity, scalability, fault tolerance, and dynamic adaptability [1]. The integration of the physical layer (microcontroller-based devices) with the high-level cloud infrastructure requires maintaining systemic consistency across the computational, network, and logical layers of architecture.

Microcontrollers are typically energy-efficient computing modules designed to perform elementary tasks of data acquisition and preliminary processing [2]. Unlike full-fledged processor systems, they possess limited resources – RAM capacity (usually up to 512 KB), clock frequency (within 80-240 MHz), no hardware support for floating-point operations, and a restricted set of peripherals. In modern distributed systems, microcontrollers are employed as edge nodes, interacting with sensor modules and actuators.

In consideration of these hardware constraints, specific focus is given to the selection of microcontroller platforms and communication interfaces to ensure a best trade-off between performance, power consumption, and cloud service compatibility. The most widely used **hardware platforms – ESP32, STM32, RP2040, and the AVR series (ATmega328P)** – offer sets of communication interfaces such as UART, SPI, I²C, Wi-Fi, BLE, and LoRa that allow direct or gateway-based connectivity with external IT infrastructure. Built-in TCP/IP functionality, combined with easy-to-access SDKs with MQTT, HTTP, and TLS support, allows for direct integration into the cloud. However, due to the restricted computational capabilities, the establishment of secure communication channels and assured data transfer require the implementation of lightweight protocols as well as retry mechanisms.

From the software point of view, these devices often run **under real-time operating systems (RTOS) such as FreeRTOS or Zephyr,** which provide support for multitasking, priority-based network stack execution, and low real-time latency. The offloading idea – offloading computationally intensive functions (e.g., encryption, buffering, analytics) to external nodes – remains a fundamental concept in designing such systems.

At the next level of integration, interaction of microcontroller devices with distributed infrastructures is offered through cloud-based IoT platforms, which form an integrated information space across the physical and logical layers of the system. These solutions offer connectivity, authentication, message routing, storage, and analytics capabilities that are the foundation for large-scale distributed systems. The most widely used IoT platforms include Amazon Web Services IoT Core, Microsoft Azure IoT Hub, which provide secure data

transmission, scalability, and integration with analytical services. Open-source solutions such as ThingsBoard, Eclipse Mosquitto, and Node-RED are also employed for flexible deployment, local processing, and edge-level autonomy.

The choice of a specific platform depends on the volume of processed data, number of devices, security requirements, latency tolerance, and deployment preferences (local or cloud). Effective integration of microcontroller devices into distributed systems is therefore possible only through harmonization of hardware capabilities, software environments, and infrastructural solutions [3]. Such an integrated approach ensures the creation of robust and adaptive architectures, capable of maintaining operational stability under varying conditions of distributed system operation.

Models of interaction between microcontroller devices and cloud infrastructure

Modern distributed systems that incorporate microcontroller-based devices require a well-designed architecture for interaction with the cloud infrastructure. The foundation of such architecture lies in various models of device-to-cloud (D2C) connectivity, which define both the logical organization of data flows and the physical distribution of system components. Depending on the specific requirements for data exchange speed, resilience, scalability, and availability, several typical architectural models are employed (fig. 1).

Figure 1. Models of typical architectural systems

The **D2C model** indicates that the microcontroller devices connect to the cloud platform with standard network protocols – usually MQTT, HTTP/HTTPS, or WebSocket [4]. In this configuration, data streams directly from the device to the cloud without passing through intermediate gateways or local servers (fig. 2).

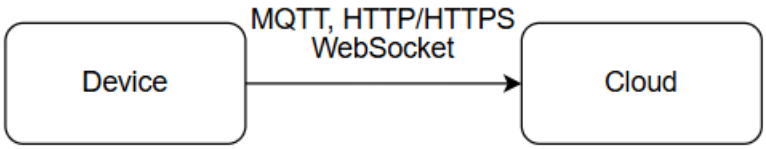

Figure 2. Architecture of the D2C model

This architecture is characterized by simplicity of implementation, low data transmission latency, and transparent routing, particularly when using commercial IoT platforms such as AWS IoT Core or Microsoft Azure IoT Hub.

Table 1 summarizes the technical parameters and typical operational characteristics of the D2C model for microcontroller-based devices communicating over Wi-Fi (e.g., ESP32) with TLS transport security. The provided values are approximate and may vary depending on the hardware configuration, network quality, and software stack parameters.

Table 1. Technical characteristics of the D2C model [5, 6]

Parameter	Typical range / value	Description
Stack resources (MQTT+TLS)	Flash: ~150–500 KB; RAM: ~40–120 KB.	Client MQTT/HTTP with TLS (e.g., mbedTLS/WolfSSL), socket buffers.
Network connection	1 TCP socket + DNS; keep-alive 30–300 s.	MQTT over TCP + TLS; periodic ping/keep-alive messages.
Cryptography / TLS	TLS 1.2/1.3; ECDHE-(ECDSA/RSA).	Handshake ~0.2–0.8 s (Wi-Fi), ~0.8–2.5 s (cellular).
Data transmission latency	Wi-Fi: ~10–100 ms; Cellular: ~100–800 ms.	For small telemetry packets under stable connection.
Payload size	100–1024 B typical; ≤4 KB practical limit.	Larger messages increase fragmentation and energy cost.
Telemetry frequency	1–10 msg/s typical; up to ~50 msg/s (Wi-Fi).	Depends on QoS 0/1 and broker/cloud configuration.
Power consumption (TX)	Wi-Fi: ~120–240 mA; deep sleep: ~10–150 µA.	Transmission phase dominates energy budget.

It should also be noted that the D2C strategy puts extra burdens on both network connection reliability and on the microcontroller performance itself. The device must handle a complete network stack, including encryption mechanisms (e.g., TLS), authentication, connection management, and data retransmission in case of failure. It is a hardware resource-intensive load, particularly on power-restricted systems with limited power supply. In addition, scaling such an architecture requires maintaining a growing number of active cloud connections, which may increase operational costs and

reduce manageability when dealing with thousands of connected devices.

In the **Device-to-Gateway-to-Cloud model,** an intermediate component – the gateway – is introduced between microcontrollers and the cloud. The gateway performs data aggregation, buffering, and, in some cases, preliminary processing [7]. Communication between devices and the gateway can be established through local interfaces such as UART, SPI, Zigbee, or BLE, thereby reducing the requirements for the microcontrollers themselves and eliminating the need to support complex network stacks (fig. 3).

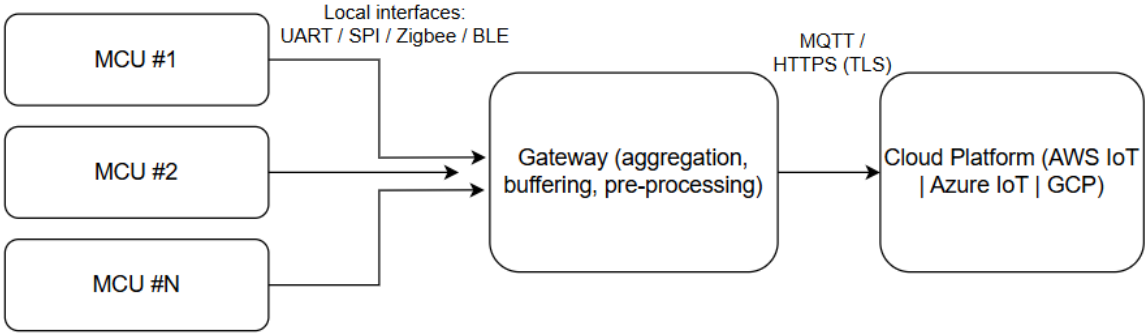

Figure 3. Architecture of the Device-to-Gateway-to-Cloud model

The gateway, with more computation capability and a more stable network connection, enables stable and secure communication with the cloud platform via session management, authentication, and message routing. This approach improves fault tolerance, allows energy-saving devices to be used, and simplifies scalability via the bundling of dozens or even hundreds of devices into logical clusters served by a single channel of communication.

The gateway-based design is also useful for facilitating local automation scenarios or data pre-processing, particularly in situations where there is untrustworthy or limited external connectivity. However, its deployment requires additional computational resources and dedicated software on the gateway side, which increases the architectural complexity of the overall system. The table below presents technical characteristics illustrating the typical parameters and limitations of such a configuration (table 2).

Table 2. Technical characteristics – device-to-gateway-to-cloud [8, 9]

Parameter	Typical range / value	Notes
Local link (MCU↔Gateway)	UART / SPI / I²C / Zigbee / BLE / LoRa	Chosen by range/bitrate/energy; MCU keeps minimal networking.
MCU resource footprint	Flash ~40–200 KB; RAM ~8–64 KB	Sensor logic + lightweight framing; no TCP/TLS on MCU.
Gateway role	Aggregation, buffering, protocol translation	Offloads TLS/QoS/retries; batches & normalizes payloads.
Security termination	mTLS (X.509) at gateway	Gateway enforces auth/ACL; optional device attestation upstream.
Reliability & buffering	Store-and-forward (seconds–hours)	Resilient to WAN outages; retry/backoff policies.
End-to-end latency	Local hop ~1–10 ms; WAN ~50–500 ms	WAN dominates E2E latency; low jitter on local hop.
Scaling	~10^2–10^4 devices per gateway	Depends on radio bandwidth, CPU/RAM, batching, QoS.

The values given are approximate and may vary depending on the hardware configuration of microcontrollers, gateway features, type of communication channel, and protocols used. A general guideline in real-world system design is to consider the destination hardware specific features, data exchange frequency, and security requirements.

The **Edge/Fog Computing model** represents an evolution of the previous architecture [10]. In this configuration, a significant portion of computations and decision-making processes is shifted from the cloud to local nodes located as close as possible to the data source – for example, on the gateway or on more powerful microcontroller-based devices equipped with RTOS and capable of performing local analytics (fig. 4).

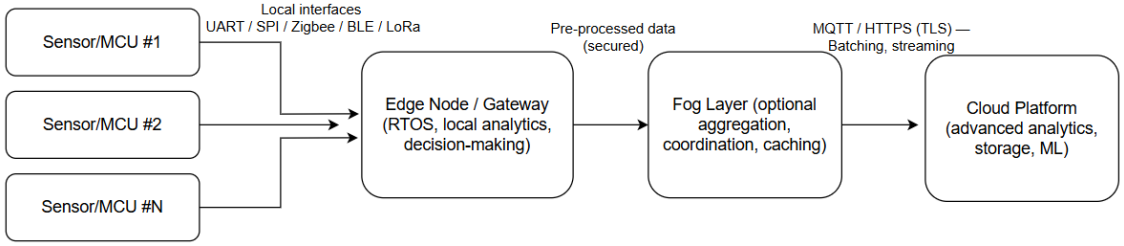
Sensor/MCU #1
Sensor/MCU #2
Sensor/MCU #N
Local interfaces
UART / SPI / Zigbee / BLE / LoRa
Edge Node / Gateway (RTOS, local analytics, decision-making)
Pre-processed data (secured)
Fog Layer (optional aggregation, coordination, caching)
MQTT / HTTPS (TLS) — Batching, streaming
Cloud Platform (advanced analytics, storage, ML)

Figure 4. Architecture of the Edge/Fog Computing model

The edge architecture enables low latency, high autonomy, and a reduction in the volume of traffic transmitted to the cloud. This is particularly important in real-time systems, including industrial automation, security systems, and transportation infrastructure. The fog computing model complements the edge model by unloading the computation tasks on a number of close-by nodes, thus providing horizontal scalability and improved system robustness.

The primary disadvantage of this model is the added computational load on the peripheral layer, necessitating the usage of more capable microcontrollers, edge servers, or single-board computers (such as Raspberry Pi). Moreover, the software infrastructure complexity increases, and more sophisticated mechanisms for data synchronization, event processing, and local decision-making are required.

Table 3 illustrates the main technical features of the Edge/Fog Computing model, duplicating the standard parameter values and functional features of this sort.

Table 3. Technical characteristics of Edge/Fog Computing architecture [11]

Parameter	Typical range / value	Notes
Edge processing capabilities	Signal filtering, feature extraction, on-device ML	RTOS-based pipelines; reduces upstream traffic.
Local inference latency	~1–20 ms (edge); end-to-end ~30–300 ms	Depends on model size, CPU/DSP/NPU, and batching.
Network dependency	Tolerant to WAN outages	Operate autonomously; sync/forward when WAN restored.
Buffering / store-and-forward	Seconds–hours on edge/fog nodes	Configurable queues, retry/backoff policies.
Security termination	mTLS (X.509) at edge/fog	Centralizes TLS, device ACLs, key rotation.
Scaling per edge node	~10^2–10^4 devices	Limited by radio bandwidth, CPU/RAM, and parsing/aggregation load.
Power impact on MCU	Lower than D2C	MCU uses short local links; heavy networking offloaded.

The presented characteristics reflect average values applicable to most implementations of the Edge/Fog Computing architecture. Specific parameters may vary significantly depending on the hardware resources of peripheral nodes, the local data processing algorithms employed, and the network interaction conditions. Overall, this model provides the optimum combination of centralized control and computation independence and is therefore best suited for real-time systems and industrial IoT applications.

The choice of a microcontroller-cloud interaction model is thus motivated by a tradeoff among architectural sophistication, response time requirements, power constraints, ownership cost, and scalability needs. In actual implementations, a hybrid model is typically used, which combines elements of various models to achieve an optimum tradeoff among performance, dependability, and economics.

Protocols and data transmission mechanisms in distributed systems

In distributed systems that integrate microcontroller-based devices with cloud platforms, the choice of data transmission protocol plays a decisive role in ensuring the reliability, security, and scalability of the entire architecture [12]. The way communication between the device and the cloud is organized determines parameters such as energy efficiency, response latency, and resilience to network failures. The most common solutions for connecting microcontrollers to the cloud include the MQTT and HTTP/HTTPS protocols, as well as message exchange infrastructures implemented through message brokers (for example, Mosquitto, RabbitMQ, and Apache Kafka) – table 4.

Table 4. Comparative characteristics of data transmission protocols

Parameter	MQTT	HTTP/HTTPS	AMQP brokers (e.g., RabbitMQ) / streaming platforms (e.g., Apache Kafka)
Communication model	Asynchronous publish/subscribe via broker.	Synchronous request/response.	Queued or stream-based, asynchronous.
QoS and reliability	QoS 0–2, session persistence.	No built-in QoS (retries at app level).	Guaranteed delivery, message persistence.
Overhead and resource use	Very low (small headers, persistent session).	Higher (HTTP headers, TLS handshake).	Moderate to high (brokers handle state and logs).
Latency and bandwidth efficiency	Low latency, efficient for small payloads.	Higher latency, larger payloads.	Slightly higher latency; high throughput.
Security mechanisms	TLS, username/password, X.509 certificates.	TLS, token-based or certificate auth.	TLS, ACL, role-based access, key management.
Scalability	Up to 10^5 clients per broker.	Limited by connection count.	Horizontally scalable (clusters, partitions).
Typical applications	IoT telemetry, sensor networks.	REST API, configuration updates.	Industrial IoT, analytics, real-time data streams.

The reliability of data exchange between microcontroller devices and cloud systems directly depends on the chosen protocol and the architectural model of interaction. In the MQTT protocol, reliability is maintained by utilizing Quality of Service (QoS) levels and the message retention feature that provide delivery assurance even in the event of temporary loss of connection. Stability in HTTP/HTTPS is offered at the transport stack and server acknowledgement levels but is less effective for streaming situations common in telemetry applications. In message broker-based systems (such as RabbitMQ or Kafka), reliability is achieved through internal logging and queuing of messages, ensuring redelivery and data consistency between distributed nodes.

Security in integrating low-level devices with the cloud requires a system-wide approach incorporating encrypted communication channels (TLS/SSL), certificate-based authentication (X.509), and access control mechanisms at gateway and broker levels. In distributed architectures, these mechanisms are complemented by centralized key management and security policy enforcement, minimizing the risk of unauthorized access. At the same time, system scalability is maintained through broker clustering, load balancing, and elastic resource allocation in the cloud, ensuring stability and performance as the number of connected devices increases [13].

The practical implementation of these protocols has found wide application in distributed IoT infrastructures developed by leading U.S. technology companies. For instance, the MQTT protocol is used in industrial monitoring systems developed by **General Electric (GE),** particularly within the Predix platform, designed for collecting and analyzing telemetry data from industrial equipment. The use of MQTT with QoS levels 1-2 allows reliable data delivery from temperature, pressure, and vibration sensors, even in the event of temporary network disruptions. Similar approaches are employed in IBM Watson IoT, where MQTT is used to connect ESP32-based microcontrollers with real-time cloud analytics services.

The HTTP/HTTPS protocol is mainly applied in enterprise IoT solutions focused on command exchange and configuration updates. For example, in **Microsoft Azure IoT Hub,** REST interfaces are used for device registration, over-the-air (OTA) firmware updates, and metadata exchange.

The use of message brokers is typical for large-scale industrial and transportation systems. For example, **Tesla** employs **an Apache Kafka-based** streaming processing infrastructure for gathering telemetry from thousands of vehicles, where each device is a node in an IoT network. The same solutions are applied in **Amazon Web Services** (AWS IoT Analytics), where RabbitMQ and Kafka brokers provide data routing and buffering between gateways and analytics services. This model ensures high scalability and message delivery guarantees even in the case of unstable networks.

Conclusion

Effective integration of microcontroller-based devices with cloud infrastructure in distributed systems requires a comprehensive approach that combines architectural flexibility, reliable data exchange, and a high level of security. The analyzed interaction models – D2C, Device-to-Gateway-to-Cloud, and Edge/Fog Computing – demonstrate different balances between computational load, scalability, and autonomy of peripheral nodes. The use of protocols such as MQTT, HTTP/HTTPS, and message brokers enables systems to adapt to a wide range of operational scenarios, from telemetry and industrial monitoring to real-time data stream analytics. Therefore, the sustainable development of distributed IoT infrastructures is achievable only through the systemic coherence of hardware, software, and network components, ensuring secure and reliable data transmission between low-level microcontrollers and high-level cloud platforms.

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DESIGN OF FAULT-TOLERANT BACKEND COMPONENTS IN MODERATION AND SEARCH SYSTEMS: PRACTICES FOR ENSURING PERFORMANCE AND AVAILABILITY

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Abstract

This article examines modern approaches to designing fault-tolerant backend components in content moderation and search systems operating under high load and within distributed architectures. The influence of microservice decomposition, data consistency strategies, and resilience patterns, such as circuit breaker, bulkhead, retry/backoff, on a system's ability to maintain availability during partial failures is analyzed. Various methods for ensuring performance and availability are investigated, and practical results of implementing fault-tolerant solutions are examined, reflecting typical behavioral characteristics of high-load systems and demonstrating how architectural choices affect the stability and quality of service operation.

Keywords: fault tolerance, high-load systems, microservices architecture, content moderation, search systems, scalability, distributed systems.

Introduction

The architecture of contemporary digital platforms must always adapt to the fast expansion of user-generated content and its growing complexity. High throughput and resilience to failures under increasing load can be essential for moderation and search systems that work with streams of various data. The fault tolerance of backend components becomes a major concern to ensuring continuous service operation in distributed computing environments with varying traffic intensity.

Modern high-load applications function in environments characterized by partial failures, network instability, and continuous resource variability. Conventional monolithic architectures are unsuitable for segment isolation and rapid incident recovery, since they are not sufficiently flexible in these circumstances. Microservice-based and cloud-native architectures partially address these problems, but the substantial increase in interacting components enhances various risks of failures and complicates consistency or state management.

The demands for user experience are also increasing at the same time. Moderation systems must detect violations promptly and make decisions within strict time constraints, while search services are expected to deliver results with minimal latency even under peak loads. The combination of requirements for performance, availability, and reliability necessitates the use of specialized architectural techniques, including resilient interaction patterns, replication strategies, approaches to eventual consistency, distributed message queues, sharding of search indexes, and self-healing services. The purpose of this article is to analyze modern architectural approaches, methods for ensuring fault tolerance, and current practical results

Main part. Architectural principles of fault-tolerant backend components

Designing for failure, or even foreseeing errors and partial outages at the architectural stage, is a determining idea when creating fault-tolerant systems. As a distributed architectural style, microservices are especially vulnerable to node failures and latency problems. Because of this, specialists aim to create robust services that integrate tried-and-true methods for preserving operational stability.

Widely used resilience patterns, such as Circuit Breaker, Retry, Fail Fast, and others, help localize failures and ensure controlled degradation of service behavior. Numerous libraries implement these mechanisms, for example, Netflix Hystrix or Resilience4J, yet their configuration and the correct interpretation of usage conditions remain nontrivial tasks [1].

The Circuit Breaker monitors the flow of errors and "opens the circuit" to a faulty service once the error threshold is exceeded, preventing cascading failures. Subsequent calls are temporarily blocked and return a predefined fallback response. This enables the system to degrade gracefully without overloading nonfunctional components. Typical implementations can be found in Spring Cloud Circuit Breaker and Envoy.

Resource isolation (Bulkhead) refers to separating computational resources or execution threads across services. By assigning distinct thread pools or containers to various services, for instance, overload in one component can be prevented from using up all system resources. As the consequence of this, a single service's failure or load spike has no effect on the others.

Retries and timeouts control transient faults such as network instability or brief service unavailability. When a request fails, the system automatically tries again multiple times with an exponential backoff interval. A timeout secures that a thread is not blocked indefinitely by limiting the overall waiting time. Although it necessitates careful configuration (too many retries could overload the system), this combination helps with recovery from shallow failures. Such retry behavior can be represented as a sequence of repeated requests in which the recovery mechanism adaptively adjusts the delay between attempts (fig. 1).

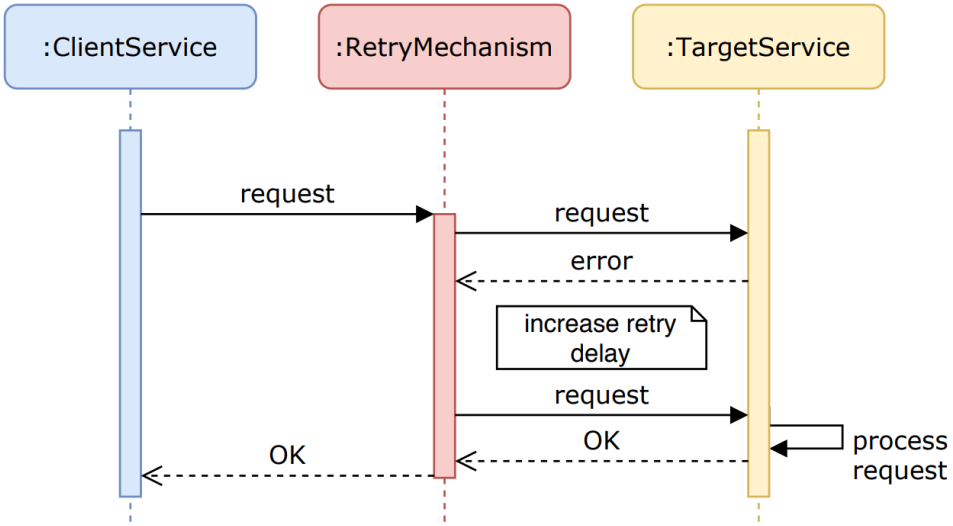

Figure 1. Retry pattern example [2]

In order to prevent bottlenecks, **load balancing** and **failover** divides incoming traffic among several nodes using algorithms like Round Robin or Least Connections. The system reduces downtime through automatically switching to backup nodes or another availability zone in the event that a node fails. Although this method improves availability, it may raise latency during cross-regional failover and present consistency issues. A typical sequence of request distribution illustrates how the load balancer ensures even utilization of service instances and maintains stable processing performance (fig. 2).

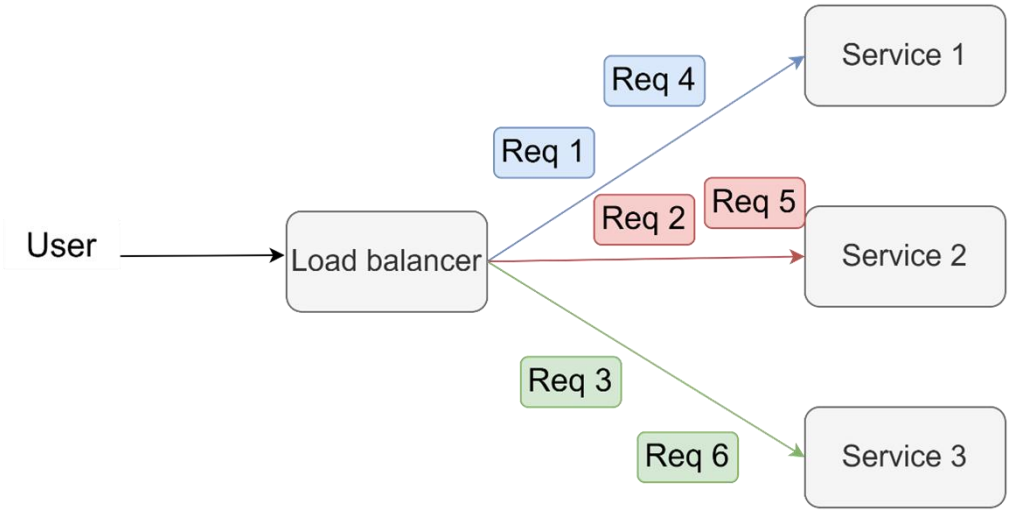

Figure 2. Example of load Balancer Routing logic

Microservices can reveal liveness and readiness probes through **health checks** and **service discovery** (Health Check/Service Discovery), allowing the platform to automatically restart or eliminate failed instances. By registering in a discovery system (like Consul, Eureka, or Kubernetes Service), services enable load balancers to direct traffic only to instances that are in good health. Maintaining resilience requires accurate calibration of these mechanisms because misconfigured probes can result in false positives.

Self-healing and **auto-scaling** are inherent capabilities of modern container orchestrators such as Kubernetes, which continuously monitor application health and automatically restart or replace failed instances [3]. They also perform automatic scaling based on load metrics: when CPU usage, task queue length, or other resource indicators increase, the system dynamically adds replicas. The combination of probes and HPA/KEDA services enables the creation of a self-recovering infrastructure. Moreover, by copying important data, geo-redundancy and data replication can guarantee fault tolerance.

These techniques and patterns collectively form the basis of an adequate fault-tolerant architecture. It is important to mindful of that all patterns are in need of careful adjustment. In multi-cloud environments, distributed replication, automated failover, and continuous testing and monitoring may be reproving to building a reliable system. To attain optimal availability and performance in actual high-load systems, these ideas are integrated into a coherent resilience strategy.

Methods for ensuring performance and availability under high load

Clusters and containers need to scale dynamically as the volume of incoming requests constantly expand. The system must modify its capacity proactively rather than reactively in high-load environments, which are

marked by erratic traffic patterns and frequent spikes in activity.

Horizontal scaling is commonly preferable to vertical scaling. Current platforms such as Kubernetes and ECS can automatically expand the number of replicas under load and reduce them during periods of low activity. Autoscaling relies on metrics such as CPU utilization, latency, and queue length, enabling the system to allocate additional resources promptly during traffic spikes.

One of the critical functions at play here is **load balancing**. Multi-level load balancers employ methodologies such as Round Robin scheduling, Fewest Connections, and geographic routing to direct traffic across the nodes. Various levels of load balancing and failover are also introduced in the architecture so that the traffic can be automatically redirected to the remaining nodes when a particular node gets overloaded. Commercial offerings such as Google Load Balancing, apart from AWS ELB/ALB and Azure Traffic Manager, direct the traffic based on the health of the instances and represent the interaction of the client, the load balancing component, and the backend platform (fig. 3).

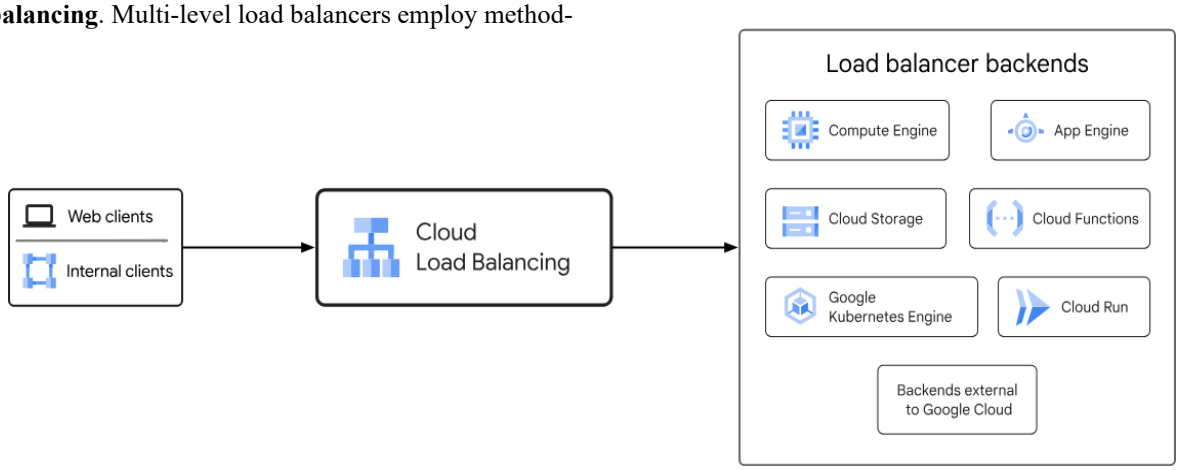

Figure 3. Google cloud load balancing overview [4]

To improve read performance, **caching and Content Delivery Networks (CDN)** are widely used. Redis and Memcached are examples of intermediate caches that speed up responses and lessen database load. Advanced caching techniques (such as write-through or write-back) and appropriate cache invalidation are crucial in distributed systems. The CDN are also widely used by websites and services to deliver static assets closer to end users.

Load spikes are mitigated by **message queues and asynchronous processing**. The system can enqueue tasks and process them as resources become available rather than stressing every microservice at once. Message brokers entitle event-driven architecture, which decouples services and offers quick scalability in the face of varying workloads.

Data distribution and sharding may be essential for expanding storage systems. Partitioning data across nodes, involving table sharding, key-based partitioning, or physical separation of indexes, is frequently used to scale relational and non-relational databases. This lessens competition for shared resources and assists the system to manage more concurrent requests. In addition, proper indexing ("effective column indexing") and caching of query results reduce database load and further improve overall performance.

Overload **control and application-level resilience** are equally important. Under excessive traffic, the system may apply backpressure, reducing the intake rate by temporarily limiting or rejecting new requests. Rate limiting and ingress queues are also used to maintain stability. Software systems frequently combine resilience patterns such as Circuit Breaker and Bulkhead to absorb traffic spikes and prevent failures in one service from cascading to others. Furthermore, monitoring and observability play a foundational role under high load. Monitoring tools (Prometheus, Grafana, etc.) track key metrics in real time (latency, error rates, CPU/memory usage) while alerts and automated triggers enable timely reactions [5].

Lastly, using pre-made solutions for hybrid cloud environments can be a practical suggestion. Managed cloud services, for instance, managed load balancers, or multi-AZ databases, and containerized workloads (Docker/Kubernetes) empower the rapid deployment of resilient clusters. The absence of a single point of failure and ongoing monitoring are all upheld in such circumstances.

Practical results of implementing fault-tolerant solutions

The practical results of implementing fault-tolerant solutions are of particular importance when assessing the effectiveness of architectural approaches and engineering methods used in high-load systems. While theoretical models and design patterns provide an understanding of how a system is expected to behave under failure conditions, it is the experimental data that reveal the actual impact of these solutions on availability, response time, peak-load resilience, and failure frequency.

Comparing the metrics of stable and non-stable configurations makes it possible to determine how the use of resilience patterns, automatic recovery mechanisms, replication, and load balancing affects availability, latency, and the system's ability to recover from failures. Analysis of aggregated data shows that even partial adoption of such mechanisms leads to a significant reduction in downtime, decreased latency, and increased predictability of system behavior under load (table 1).

Table 1. Comparative performance metrics [6]

Metric	Resilient system	Non-resilient system	Improvement (%)
System Availability (%)	99.96	97.8	2.21
Mean Time to Recovery (MTTR)	42 sec	208 sec	-79.81
Mean Time Between Failures	58 hrs	24 hrs	141.67
Avg. Response Time (p95)	310 ms	790 ms	-60.76
SLA Breach Rate (%)	0.3	4.8	-93.75

Moreover, the transition to a microservices architecture demonstrates in practice how decomposition and distributed execution improve a system's resilience and predictability under load. Earlier, a transformation of a traditional monolithic e-commerce application into a microservices-based system was presented, and the results showed a substantial advantage of microservices in terms of latency and processing stability as traffic intensity increased (table 2).

Table 2. Performance results – response times [7]

Test case	Average microservice	Average monolith	90% percentile microservice	90% percentile monolith
Test case 1	12 ms	14 ms	19 ms	16 ms
Test case 2	13 ms	29 ms	19 ms	21 ms
Test case 3	16 ms	308 ms	26 ms	1256 ms
Test case 4	197 ms	1075 ms	610 ms	2032 ms
Test cases explanation				
Number of the case		Number of users	Repetitions	Ramp-up
Test case 1		1	1000	1
Test case 2		5	100	5
Test case 3		20	100	10
Test case 4		50	150	30

It is evident that as the load grows (as seen in Test 4), the monolithic system begins to respond an order of magnitude slower: an average of 1075 ms compared to 197 ms in the microservices-based system (with 90th-percentile values of 2032 ms versus 610 ms). At the same time, microservices are distributed across multiple machines, keeping the CPU load of each instance relatively low (~50%), whereas the monolith reaches its processor limits (100%).

Similar observations are reported in other practical studies. Zhang et al. (2025) proposed a microservice architecture based on Spring Cloud and Docker, incorporating adaptive load balancing and multiple levels of fault tolerance. Their experiment showed that such a system delivered approximately 20% higher QoS compared with the monolith and outperformed the standard Spring Cloud implementation in throughput, achieving around 2942 requests per minute in JMeter tests [8]. The recovery time after a failure was less than 5 seconds, indicating rapid convergence of the failover mechanism.

Furthermore, engineering reports from major companies indicate similar trends. For example, when migrating to fault-tolerant, multi-regional deployments, many organizations report a substantial reduction in downtime and improved user satisfaction (99.99%+ SLA). Self-healing mechanisms are widely used in Chaos Engineering practices, where controlled fault injection in test environments has shown that regularly exercising failure scenarios helps identify weaknesses before they manifest in production [9].

The implementation of fault-tolerant architectural solutions has a direct and measurable impact on the performance of high-load moderation and search systems. Increased availability, reduced response times, fewer SLA violations, and faster recovery after failures are consistent effects observed when mechanisms such as scaling, replication, load balancing, and resource isolation are applied.

Conclusion

The architectural principles of fault tolerance in moderation and search systems rely on a comprehensive approach that encompasses microservice decomposition, resilient communication patterns, flexible data-consistency strategies, and well-designed processing pipelines. Microservices enable failure isolation and independent scaling of components but require mature resilience patterns such as circuit breaker, retry/backoff, bulkhead, and idempotency.

Choosing appropriate models of consistency and availability within the framework of the CAP theorem helps balance data freshness with high service availability. Data-processing pipelines in moderation and search impose different resilience requirements: moderation workflows rely on message queues and asynchronous pipelines, whereas search systems depend on indexing, replication, and distributed query processing. Together, these architectural choices form the foundation for highly reliable systems capable of sustaining large traffic volumes, multiple points of failure, and dynamically changing operational conditions.

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INTELLIGENT EARLY WARNING SYSTEMS FOR FINANCIAL RISKS IN THE SHIPBUILDING INDUSTRY: A MACHINE LEARNING-BASED APPROACH

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Abstract

The article examines the problem of early detection of financial risks in the shipbuilding industry, which is characterized by high capital intensity, long production cycles and increased sensitivity to macroeconomic instability. It analyzes the potential of intelligent systems based on machine learning methods for proactive monitoring of managerial and accounting data. The role of adaptive algorithms in identifying hidden patterns, anomalies and pre-crisis states emerging long before their actual manifestation is emphasized. The article discusses architectural principles for designing a multi-layer modular platform, issues of integration with corporate information systems and the algorithmic support of the analytical layer. The practical significance of intelligent early warning systems for improving forecasting accuracy, stabilizing financial flows and enhancing the effectiveness of crisis management in shipbuilding enterprises is substantiated.

Keywords: shipbuilding, financial risks, machine learning, intelligent systems, predictive analytics, early warning, crisis management.

Introduction

The modern shipbuilding industry is one of the most capital-intensive and technologically complex sectors of manufacturing, exposed to a wide range of external and internal sources of financial instability. Prolonged production cycles, a high share of advance payments on projects, and dependence on government policy and global logistics chains make the industry particularly vulnerable to financial risks. Under conditions of increasing uncertainty in the macroeconomic environment, exchange-rate volatility, rising resource costs, and instability of supply chains, there is a growing need for proactive tools for monitoring and analyzing the financial condition of enterprises. One of the promising directions is the use of intelligent systems based on machine learning (ML) algorithms, capable of detecting latent patterns in management and accounting data flows and generating signals of potential deviations long before they are actually realized.

The relevance of this study is determined by the need to develop technologically adaptive solutions that provide early warning of financial risks, enhance the resilience of shipbuilding enterprises, and improve the effectiveness of crisis management. The aim of this work is to analyze a conceptual model of an intelligent financial risk warning system in shipbuilding, based on ML methods and integration with corporate information flows. The study focuses on formalizing an approach to the processing of management information, selecting effective analysis algorithms, and substantiating the practical applicability of the proposed tool in the context of industry-specific constraints and requirements.

Main part. Structural and economic characteristics of the shipbuilding industry

Shipbuilding is one of the most capital-intensive and organizationally complex branches of industry, characterized by a high concentration of labor-intensive and material-intensive processes, as well as a pronounced dependence on government orders and macroeconomic conditions [1].

The high level of capital intensity in shipbuilding is confirmed by the scale of the global market. According to DataBridge, it was estimated at $145.65 billion in 2024 (fig. 1).

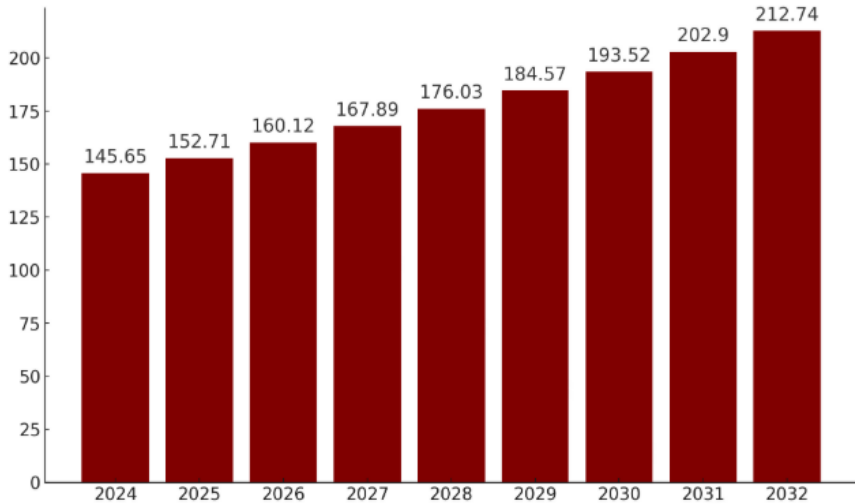

Figure 1. Forecast of the dynamics of the global shipbuilding market volume in 2024–2032, billion dollars [2]

The key characteristics of the shipbuilding industry include long production cycles, the need for upfront financing of projects at early stages, a high share of work in progress, and a project management framework oriented towards individual technical specifications. In view of this, enterprises in the sector are exposed to significant operational and investment risks arising both from the external economic environment and from internal managerial decisions.

The financial risks inherent in the shipbuilding industry are shaped by the combined influence of external macroeconomic factors and internal operational processes. The main sources of financial instability in shipbuilding are summarized in table 1.

Table 1. Major sources of financial risk in the shipbuilding industry [3, 4]

Risk type	Description	Potential consequences
Price risk	Fluctuations in the cost of raw materials, metals, components, and contractor services.	Increased production costs, budget overruns, reduced project margins.
Currency risk	Exchange rate volatility affecting imports and export-oriented contracts.	Revaluation of liabilities, conversion losses, profit margin variability.
Credit risk	Payment delays or defaults by customers or supply chain partners.	Increased accounts receivable, cash flow disruptions, decreased liquidity.
Operational risk	Failures in internal processes, human errors, or planning deficiencies.	Schedule delays, delivery failures, penalties.
Project-specific risk	Technical issues, changes in specifications, or cost escalations due to redesigns.	Project timeline extensions, budget overruns, loss of competitiveness.
Regulatory and sanctions risk	Impact of regulatory changes, sanctions, and restrictions on technology access.	Contract suspensions, import/export limitations, increased compliance costs.
Logistics risk	Delays in the supply chain or transportation of components.	Production downtime, construction schedule disruptions.
Concentration risk	Dependence on a limited number of customers or suppliers.	Loss of key clients, revenue volatility, unfavorable renegotiation conditions.

Reliable and timely detection of potential deviations is possible only if robust mechanisms are in place for analyzing both accounting and management information. Within the data flows circulating in shipbuilding companies, the key sources for monitoring the financial situation are cash flow statements, project budgets, cost calculations, information on accounts receivable and payable, as well as internal operational reports. However, such data are often presented in a fragmented form, with a low degree of standardization, and may be received with time lags, which complicates their analysis by traditional methods.

In this context, the use of intelligent analytical systems capable of automatically processing large volumes of heterogeneous information and identifying anomalies in indicator behavior patterns becomes highly relevant. This approach is consistent with current trends in the digitalization of corporate governance, which are characterized by a shift from static reporting to proactive predictive analytics systems. Similar technologies have already demonstrated their effectiveness in other domains, for example in corporate cybersecurity solutions based on Zero Trust models that can respond to non-standard actions in real time [5].

Thus, the shipbuilding industry requires specialized approaches to the processing of management and accounting information that take into account industry-specific features and the need for resilience to financial risks. The application of ML methods in this field can not only improve forecasting accuracy, but also provide a foundation for the formalization and automation of crisis management processes.

Conceptual foundations for designing an intelligent early warning system

The development of an intelligent early warning system for financial risks in the shipbuilding industry requires a comprehensive approach that combines methods of applied mathematics, ML and business process engineering. Under conditions of high complexity and fragmentation of financial and managerial information, primary attention is given to designing an architecture that ensures continuous acquisition, cleansing, analysis and interpretation of data in a mode close to real time [6]. The purpose of such a system is to generate managerial signals about potential deviations long before they actually materialize, thereby enabling preventive measures and minimization of losses.

Architecturally, the system can be represented as a multi-layer modular platform comprising four functional blocks (fig. 2).

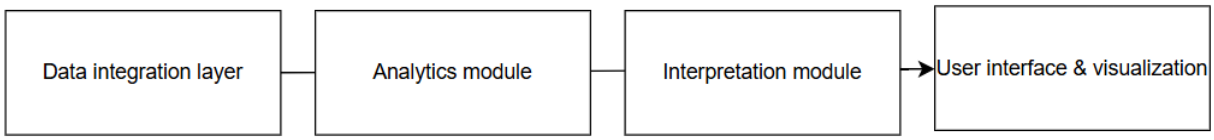

Figure 2. Architecture of the multi-layer modular platform

At the first architectural level, the **data integration layer** provides continuous automated collection and synchronization of information from the company's internal information systems and from external sources. This module creates a unified digital data

space, eliminates heterogeneity of formats, ensures the comparability of indicators over time and forms the basis for the stable operation of the analytics layer. Integration with the existing digital infrastructure of the enterprise makes it possible to embed the intelligent system into current management cycles without disrupting ongoing business processes, which is consistent with modern requirements for adaptability and flexibility of business platforms [7].

The **analytics module implements algorithms** for identifying patterns and forecasting deviations in key financial indicators, including cash gaps, payment delays, cost escalation, deterioration of payment discipline and other critical parameters. To increase the robustness of the analysis to noise and unstable data structures, ensemble ML methods (XGBoost, CatBoost), recurrent neural networks of the LSTM type for processing time series, and clustering methods (DBSCAN, k-means) are applied to detect atypical behavioral scenarios.

The **interpretation module transforms** the results of machine analysis into a form that is meaningful for managerial decision-making. For this purpose, explainable AI techniques such as SHAP and LIME are used to determine the contribution of individual factors to the formation of forecast risk estimates and to provide a transparent explanation of the causes of identified deviations. This increases trust in the modelling results and creates a basis for their practical use within the corporate risk management system.

The **user interface and visualization module** presents the analysis results in the form of dashboards, risk indicators and notification mechanisms for different management levels. At this level, both real-time alerting on critical deviations and support for expert assessment in the planning of anti-crisis measures are implemented. Thus, the intelligent system operates as an independent analytical layer between data sources and the management decision support system, providing both automatic responses and integration with strategic management processes.

Algorithmic framework of the intelligent system based on ML methods

Forecasting financial risks in the shipbuilding industry requires the use of adaptive algorithms capable of capturing the high dynamism and nonlinearity of processes reflected in managerial and accounting data. The development of the algorithmic core of an intelligent early warning system is based on ML methods that allow for the identification of hidden patterns, anomalies, and precursors to financial instability. The methodological selection of models is driven by the need to handle heterogeneous data with varying temporal resolution, as well as by the requirements for interpretability and forecast robustness (table 2).

Table 2. Comparative overview of ML algorithms for financial risk forecasting [8, 9]

Algorithm	Description and characteristics	Advantages	Limitations
XGBoost / CatBoost	Gradient boosting on decision trees; effective with tabular, structured datasets.	High accuracy, outlier tolerance, automatic handling of categorical features.	Less suitable for long-term time-series modeling.
LSTM (Long Short-Term Memory)	Recurrent neural networks designed for sequential data and temporal dependencies.	Captures delayed effects, ideal for time-series forecasting.	Requires large datasets; complex and less interpretable
Random Forest	Ensemble of decision trees with bootstrap aggregation.	Easy to tune, robust to overfitting, interpretable.	Limited performance on long-range temporal dependencies.
Logistic Regression	Classical statistical method for binary classification.	High interpretability, low computational cost.	Poor performance with nonlinear or complex relationships.
K-means / DBSCAN	Clustering algorithms for grouping similar observations and detecting anomalies.	Useful for segmentation and outlier detection.	Not predictive by nature; requires additional processing for decision-making,

While table 2 summarizes the main families of ML algorithms applicable to financial risk forecasting, the practical implementation of these models within an intelligent early warning system requires a strict formalization of the data architecture. In particular, it is necessary to clearly define which categories of managerial and accounting data are treated as input features, how unstable financial states are represented in the form of target variables, and which types of output signals are generated for managerial decision support. Without such formalization, the predictive models remain isolated analytical tools and cannot be fully integrated into the corporate risk management loop. For this reason, the logical structure of input indicators, target variables and output risk signals used in the proposed system is systematized in table 3.

Table 3. Key input data, target variables and output signals of the intelligent early warning system

Data group	Specific variables	Role in the model
Cash flow indicators	Planned and actual cash inflows and outflows, net cash flow.	Detection of liquidity gaps and cash flow disruptions.
Budget performance	CAPEX and OPEX deviations, project-level cost overruns.	Forecasting probability of budget overruns.
Accounts receivable	Turnover period, share of overdue receivables.	Assessment of non-payment and liquidity risk.
Production utilisation	Capacity utilization rates, workload coefficients.	Linking operational risks with financial instability.
Target variables	Occurrence of crisis event, liquidity drop, payment default.	Supervised model training.
Output risk signals	Risk score, probability of financial instability, alert level (low/medium/high).	Generation of early warning alerts.

The model-building process begins with the construction of training datasets consisting of aggregated and transformed indicators across key projects and organizational units. The source data include time series such as funding volumes, accruals and payments, budget deviations, average receivables turnover periods and resource utilization rates. To improve model quality, preprocessing steps such as normalization, imputation of missing values and decomposition of trends and seasonal components are applied. Special attention is paid to the generation of target variables reflecting the onset of unstable conditions (e.g., a sharp liquidity decline or persistent cost overruns), as well as to feature engineering, including derived indicators, lagged variables and moving aggregates.

The selection of specific algorithms is based on empirical comparison of prediction accuracy and resilience to overfitting. For temporal risk forecasting, recurrent neural networks (LSTM/GRU) are applied due to their ability to model sequential dependencies and delayed effects. Gradient boosting algorithms (XGBoost, LightGBM, CatBoost) have proven highly effective for classification and regression tasks, particularly in estimating the probability of a financial risk event within a defined time window. In cases where data availability is limited or interpretability is a priority, models such as Random Forest and logistic regression are also employed.

Similar to how geographic information systems (GIS) have demonstrated their capacity to enhance operational efficiency in maritime transportation through the integration of complex, spatially distributed data [10], ML algorithms in shipbuilding can serve to synthesize diverse financial indicators for early identification of instability.

To enhance user trust and ensure managerial interpretability, explainable AI (XAI) techniques such as SHAP are applied. They make it possible to determine which factors, for example overdue receivables or declining inventory turnover, have the greatest impact on the forecast. On this basis, the system generates alerts and scenario-based warnings visualized via interactive dashboards with configurable thresholds and integrated notification mechanisms.

The inclusion of explainable AI techniques is particularly important in corporate environments where transparency and traceability of decision-support systems are essential, especially when external audit mechanisms are integrated into risk management frameworks [11].

In summary, the algorithmic framework of the intelligent early warning system combines advanced ML tools with the applied logic of financial risk control. This enables timely detection of emerging threats and supports the transition from reactive to proactive crisis management strategies grounded in quantitative indicators and reproducible analytical procedures.

Evaluation of effectiveness and practical implementation results

The effectiveness of an intelligent early warning system for financial risks in shipbuilding should be assessed using a combination of quantitative and qualitative criteria. At the **ML model level**, the key metrics include the accuracy of classifying pre-crisis states, sensitivity to rare events (recall for the “risk” class), the stability of forecasts across different time horizons, and the interpretability of individual factor contributions. Notably, in a related maritime segment – logistics and shipping – the use of ensemble models (in particular, the random forest algorithm) for financial early warning achieved an accuracy of 80.52 % on the test sample, outperforming logistic regression (74.03 %) and neural network models (79.20 %) [12]. These results demonstrate that well-tuned ML algorithms are capable of generating statistically reliable signals of financial instability, which can be adapted to the task of early detection of risks in shipbuilding projects.

At the **managerial level**, the effectiveness of such systems is evaluated in terms of reduced dispersion of cost and schedule forecasts, lower frequency and magnitude of budget overruns, and stabilization of key Earned Value Management indicators (CPI, SPI). The experience of major shipbuilding programs in the United States shows that integrating analytics based on ERP, EVMS, schedule management systems and production systems (MES, PLM) makes it possible to keep CPI/SPI indices within a narrow corridor around 1.0 (±0.05) and to constrain the deviation of Estimate at Completion (EAC) forecasts to within ±5 % at the program level [13]. This level of predictability is feasible only when robust mechanisms for early detection of deviations are in place and financial forecasts are tightly linked to the actual progress of work, which conceptually aligns with the objectives of the proposed intelligent system.

Individual examples of AI-based solutions implemented in US shipbuilding companies demonstrate measurable economic effects and confirm the feasibility of using predictive analytics as the core of early warning. For instance, the **Shipyard AI** software suite developed by **BigBear.ai,** deployed at a large US shipyard, enabled the integration of four production sites into a unified planning system, reduced schedule-generation cycle time by approximately a factor of four, and yielded savings of about $975,000 in the first year solely due to optimized scheduling [14]. Although this example is primarily focused on capacity loading and schedule management, it clearly shows that modelling, forecasting and anomaly-detection algorithms can significantly reduce managerial inertia and create a foundation for early identification of both temporal and financial deviations.

Major American shipbuilding corporations such as **Huntington Ingalls Industries (HII) and the General Dynamics yards Bath Iron Works, Electric Boat and NASSCO** are actively implementing a "digital shipyard" strategy based on digital twins, integrated PLM systems and AI-driven analytics. In particular, HII, in cooperation with C3 AI, is expanding the use of AI solutions to accelerate ship construction and optimize supply chains. These initiatives contribute to higher productivity and shorter production cycles, while for the financial domain they enable earlier detection of adverse performance trends that directly affect cost growth and serve as input signals for early warning systems.

Given these examples, the evaluation of the effectiveness of the proposed intelligent system in shipbuilding can be structured into several groups of indicators. First, **model quality metrics**: the accuracy and completeness of pre-crisis state detection, the proportion of false alarms, and the temporal stability of model parameters. Second, **managerial indicators:** reduction in the average deviation of actual cost from planned cost, lower frequency of budget overruns beyond a specified threshold, reduced dispersion of EAC forecasts relative to actual values, and increased stability of CPI/SPI within target corridors comparable to industry best practices. Third, **time-related indicators**: extension of the average "warning horizon" (the interval between a system signal and the actual occurrence of a crisis event) and reduction in the time required to prepare management reports and scenario analyses. The validation approach should be aligned with corporate risk management and external audit principles, which place significant emphasis on the reproducibility of estimates and the transparency of the rationale for conclusions.

The analysis of international experience in the digital transformation of shipyards confirms the high practical relevance of intelligent early warning systems for financial risks. Their use contributes to improved forecasting quality, shorter management response times and a shift from a reactive management model to a proactive one focused on preventing crisis situations.

Results of empirical validation and effectiveness analysis

While the above indicators provide a structured framework for evaluating the effectiveness of intelligent early warning systems at both the model and managerial levels, their practical relevance ultimately depends on empirical validation under real operational conditions. Accordingly, it is appropriate to conduct empirical validation and methodological refinement of financial risk forecasting approaches for shipbuilding enterprises.

Within the **applied experiments with ML models direction**, project-level financial datasets were used to compare ensemble boosting methods (XGBoost and CatBoost) with classical logistic regression, and model performance was evaluated using standard classification metrics. The evaluation employed standard metrics:

$$\text{Accuracy} = \frac{\text{TP+TN}}{\text{TP+TN+FP+FN}}, \text{Recall} = \frac{\text{TP}}{\text{TP+FN}}, \text{Precision} = \frac{\text{TP}}{\text{TP+FP}}, \quad (1)$$

Results indicated that gradient boosting achieved an accuracy of 0.87 and recall of 0.81 for early detection of liquidity gaps, compared to logistic regression (accuracy 0.75, recall 0.68). This extended the average "warning horizon" by 2–3 weeks, allowing managers to anticipate cash flow disruptions earlier.

Within the **prototype development in collaboration with Engineering Services** direction, a pilot analytical module was designed and embedded into the ERP environment of an engineering services company specializing in shipbuilding analytics and financial risk management. The system implemented anomaly detection on receivables turnover:

$$\text{DSO} = \frac{\text{Accounts Receivable}}{\text{Total Credit Sales}} \cdot 365, \quad (2)$$

where DSO (Days Sales Outstanding) served as a leading indicator of liquidity risk. Automated alerts were triggered when DSO exceeded a dynamic threshold:

$$\text{Threshold} = \mu_{\text{DSO}} + 2\sigma_{\text{DSO}}, \quad (3)$$

with μ_{DSO}= mean turnover period and σ_{DSO}= standard deviation. This reduced reporting preparation time from 5 days to 1 day and enabled proactive supplier negotiations. Managers at the engineering services firm reported that the system's alerts allowed them to intervene in supplier contracts and payment scheduling before problems escalated, demonstrating the feasibility of integrating intelligent early warning systems into engineering services for shipbuilding.

As a **methodological innovation**, a **hybrid modelling framework** was introduced that combines machine learning–based forecasting with rule-based anomaly detection. For time-series forecasting, LSTM networks were applied:

$$h_t = f(W_{xh}x_t + W_{hh}h_{t-1} + b_h), y_t = W_{hy}h_t + b_y, \quad (4)$$

where $h_t$is the hidden state, $x_t$the input features, and $y_t$the predicted risk score. This was complemented by SHAP-based explainability:

$$\text{Prediction} = \phi_0 + \sum_{i=1}^{M} \phi_i, \quad (5)$$

where $\phi_i$represents the contribution of feature ito the forecast. Managers could thus trace risk signals back to specific drivers such as overdue receivables or declining capacity utilization.

Beyond the achieved technical and analytical results, it appears necessary to embed financial risk monitoring mechanisms into the broader digital shipyard ecosystem by aligning predictive analytics with PLM, MES and digital twin technologies. Such integration enables the formation of a holistic resilience framework in which operational and financial signals are treated as interdependent components of a unified management system. This approach can be considered a promising direction for establishing intelligent early warning systems as a standard element of proactive crisis management in the shipbuilding industry.

Conclusion

Intelligent early warning systems for financial risks based on ML methods represent a promising tool for enhancing the resilience of shipbuilding enterprises under conditions of high capital intensity, long production cycles and external economic uncertainty. Their application enables a transition from fragmented and delayed control to continuous proactive monitoring of the financial condition, allowing adverse trends to be detected in a timely manner and well-grounded managerial decisions to be formed. The integration of such systems into corporate infrastructure creates a technological foundation for improving the effectiveness of crisis management, reducing the likelihood of critical deviations and strengthening the financial stability of shipbuilding companies.

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